A CAVITATING WATER JET CLEANING SYSTEM FOR REMOVING MARINE GROWTH AND FOULING FROM OFFSHORE PLATFORMS

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A. P. Thiruvengadam

December 1979

The work described herein was sponsored by the Research and Development Program for OCS Oil and Gas Operations, USGS, under contract to the Office of Naval Research. Though this document is the final report for a diver held cavitation erosion cleaning device which is pressurized from the surface, the feasibility of a self contained power supply is now under study.

If you wish to comment on the research or desire further information, please contact the authors or USGS.

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FINAL REPORT

THE RESEARCH AND DEVELOPMENT OF A CAVITATING WATER JET CLEANING SYSTEM FOR REMOVING MARINE GROWTH AND FOULING FROM OFFSHORE PLATFORM STRUCTURES

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The objective of this program was to develop the technology to demonstrate the use of controlled cavitation erosion to remove marine growth from offshore structures. The major advantage of a cavitation system would be the smaller energy input requirement. Commercial systems are available but they require three to four times the energy in order to accomplish the same task. Through the use of cavitation technology small, lightweight components which will conserve energy can be utilized. (continued)

The following engineering parameters were evaluated in order to demonstrate the use of controlled cavitation erosion, CONCAVER™, technology: (1) nozzle distance (Dn); (2) nozzle design; (3) nozzle velocity (Vo); (4) intensity of cavitation erosion (I_e); (5) water depth (d); and (6) nozzle horsepower (HP_m). The family of data curves were gathered which allowed optimization of the test conditions and equipment in order to obtain the maximum cleaning rate. Once the most effective nozzle design was determined, the other parameters were evaluated both in the laboratory and in field tests in order to maximize the surface area cleaned with respect to time. This report addresses the work accomplished which resulted in field test cleaning rate data which illustrated that:

1. The CONCAVER technology was capable of removing marine growth to a bright metal finish at the rate of 60 square feet per hour.
2. The CONCAVER technology was capable of cleaning a 42 inch diameter marine propeller in 30 minutes. When extrapolated to a standard Navy propeller this would mean a 12 foot diameter propeller could be cleaned in 6 hours.
3. The CONCAVER technology was utilized to clean marine growth from the structure without damage to the substrate protective tar coating at approximately 400 square feet per hour.

These field test results were obtained with a 2.25 gpm flow rate at an operating pressure of 9,000 psi or less. The nozzle input horsepower was less than 20 hp. The maximum in-water reactive force created at the nozzle by the pressure/flow combination was always less than 7 pounds as compared to a commercially available system with a thrust of approximately 25 pounds. The commercial system used a thrust compensation device to ease the load on the operator. This compensation was not required with the CONCAVER system.

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ABSTRACT

The objective of this program was to develop the technology to demonstrate the use of controlled cavitation erosion to remove marine growth from offshore structures. The major advantage of a cavitation system would be the smaller energy input requirement. Commercial systems are available but they require three to four times the energy in order to accomplish the same task. Through the use of cavitation technology small, lightweight components which will conserve energy can be utilized.

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THE RESEARCH AND DEVELOPMENT OF A CAVITATING WATER JET CLEANING SYSTEM FOR REMOVING MARINE GROWTH AND FOULING FROM OFFSHORE PLATFORM STRUCTURES

1.0 INTRODUCTION

Inspection of offshore structures for the purpose of detecting structural degradation prior to a catastrophic failure could potentially save both lives as well as millions of dollars in equipment. Several countries throughout the world have established regulations for inspection and maintenance of structures in their offshore waters. The U. S. Geological Survey is embarked upon an offshore structural verification program and, although underwater inspection is not likely to be required of industry in the near future, the technology developed in this research program should prove helpful to industry and to anyone assessing the problems of cleaning fouling from structural joints.

As offshore structures approach design life during in-service utilization, it is imperative that proper inspection procedures be employed. The various procedures presently being used in the field require an efficient method for cleaning offshore structures before these nondestructive evaluation techniques can be effectively used for crack detection as a measure of platform deterioration. Furthermore, corrosion mechanisms including crevice corrosion and pitting are initiated by the attachment of marine organisms. Periodic cleaning of offshore platform structures would reduce the corrosion rates and increase the service life of these structures thereby enhancing the safety and reliability of in-service operations.

The complex nature of the structural sections including "I" sections, angles, channels, joints, weldments, nuts, and bolts makes it difficult and time comsuming for divers to use conventional brushes for removing marine organisms. Some of the organisms produce strong calcareous cements which are very difficult to remove, even by wire brush techniques. As a result, there is an urgent need to develop an effective, simple and economic method to clean the marine growth from offshore structures.

With these objectives in mind, DAEDALEAN ASSOCIATES, Inc. has been experimenting with the utilization of the phenomenon of Controlled Cavitation Erosion (CONCAVER™) as a technique for cleaning offshore structures. The CONCAVER technology has been under investigation for approximately five years as a tool to do useful work (1, 2).* Under the cooperative funding of the Office of Naval Research and the United States Geological Survey, efforts to demonstrate this technique as a tool for removing marine fouling were undertaken.

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* Numbers in parentheses refer to references at the end of this report.

2.0 BACKGROUND AND OBJECTIVES

Phase I of this research program was the initial feasibility study. Under this phase of the program several different nozzle designs were evaluated in order to determine the threshold intensity of erosion for marine fouling, the marine antifouling paint and the steel base platform material. Once these factors were determined, three different nozzle designs were used to define cleaning rates and horsepower requirements in order to remove fouling to a bright metal finish. The feasibility portion of this program was able to define the data needed to proceed with the nozzle optimization in Phase II.

The threshold intensity of erosion for marine fouling was determined to be 450 watts/meter^2 (w/m^2). The nozzle which proved to be most efficient at fouling removal was the 0.031 inch diameter standard ASTM orifice design. This nozzle developed a peak intensity of 12,100 w/m^2 as illustrated in Figure 1. For this nozzle configuration, a cleaning rate to a bright metal finish of approximately 16 ft^2/hr was obtained for a requirement of 22 horsepower. This data was obtained at a nozzle pressure of 14,000 psi. One major drawback was observed. The maximum width of a single pass to clean a surface was determined to be 1/8 inch at a nozzle standoff distance of 1 inch.

With these accomplishments as motivation, the second phase was initiated. The objective of this portion of the program was to advance the cavitation technology to obtain maximum cleaning capability and demonstrate this capability under field conditions. Two major areas of investigation were used to accomplish this goal. The first was the evaluation of additional nozzle designs in order to maximize the cleaning rate, reduce the operating pressure and minimize the power requirement. The second area was to establish the effect on intensity of erosion and cleaning rate for water depths up to 150 feet.

3.0 EXPERIMENTAL APPARATUS AND TECHNIQUES

3.1 Laboratory Equipment

Equipment used for the evaluation of the CONCAVER technology as a method of removing marine fouling consists of: a triplex plunger pump/motor combination; a pressure chamber; a velocity calibration chamber; and a traverse mechanism. Each of these items was used in one or more of the experiments conducted. In addition, for the cleaning rate determinations, plate samples were obtained with barnacle growth on them which simulated typical fouling conditions.

The triplex plunger pump was used in all of the experiments as the high pressure water supply. The pump was capable of developing 15,000 psi operating pressure and was rated at 4 gallons per minute (gpm) flow rate at that pressure. Figure 2 is an illustration of that pump. A second speed condition was available which increased the pressure capability but this capability was not required for these experiments.

The velocity calibration chamber was used to develop the velocity profile for each nozzle with respect to pressure. The test nozzle was mounted inside the chamber and the flow from the chamber was measured. This flow condition was measured for each 1,000 psi increment from 0 to 15,000 psi. Figure 3 is the concept drawing of the velocity calibration chamber.

The pressure chamber shown in Figure 4 was used in two different experimental configurations. The first test condition was the intensity of erosion data acquisition. In these tests, the intensity of cavitation erosion for each nozzle was established with respect to nozzle distance and nozzle pressure. The other test condition was the evaluation of the effect of water depth. The controls associated with the pressure chamber allowed tests of simulated water depths. These simulations were created by controlling the hydrostatic pressure inside the chamber. The chamber was capable of pressures up to 1,500 psi. This range of pressure would permit depth simulations equivalent to approximately 3,500 feet.

The final piece of nozzle evaluation laboratory apparatus was the traverse mechanism. Figure 5 illustrates the equipment used to traverse the fouled samples past the nozzle. This equipment was used to perform cleaning rate tests and establish cleaning rates as a function of pressure and nozzle distance.

3.2 Field Equipment

In order to demonstrate the ability of the CONCAVER technology to function under field conditions, field test equipment was assembled. This equipment included a field pumping system, a hose reel and rotary seal assembly, lightweight flexible high pressure hose, and a diver operated gun for use with the selected cleaning nozzles.

The laboratory data indicated that a low flow, high pressure pump was optimum for use with either nozzle design. However, that type pump was not a commercially available item. In order to supply water at the required pressure, a pump similar to the laboratory pump was obtained. This pump was rated for 10,000 psi pressure and 10 gpm flow rate. A manually operated flow control valve was installed so that the flow to the gun could be maintained at the nozzle design flow. Figure 6 is a photograph of that pumping unit as it was installed on the vessel used for field operations.

In order to make the operation of the underwater equipment more convenient for the diver, a lightweight flexible hose was obtained. This hose had an inside diameter of 1/4 inch and a burst pressure rating of 26,000 psi. With field tests planned for pressures of 10,000 psi or less this gave a safety factor of 2.6 for the hose. In order to utilize the hose effectively, the hose was mounted on a reel. The reel was equipped with a rotary seal which allowed the drum to rotate while the high pressure supply from the pump remained stationary. Figure 7 shows the flex-hose, hose reel and rotary seal assembly as used in the field tests.

The last item of field equipment is the gun. The gun was designed to be lightweight, safe, comfortable and require no thrust compensation device. Manufactured of a titanium alloy (3), the gun was resistant to the effects of sea environment and lightweight while maintaining an excellent strength to weight ratio (4). Figure 8 illustrates the gun in its disassembled state which shows all component parts. Figure 9 shows the gun attached to the flex-hose ready for operation.

3.3 Laboratory Procedures

Each nozzle was tested and evaluated in terms of five major nozzle performance parameters. These factors included:

1. Nozzle velocity, V_o, (in fps)

2. Loss coefficient, C_v, (nondimensional)
3. Intensity of cavitation erosion, I_e, (w/m^2)
4. Nozzle horsepower, HP_m, (horsepower)
5. Cleaning rate (ft^2/hr)

The nozzle parameters were optimized with respect to nozzle distance (D_n), nozzle pressure (P_o), and nozzle design. The accumulated test data included the velocity calibration, and the intensity calibration.

The orifice diameter of each nozzle was accurately measured as an initial step. This information was important for technical documentation as well as velocity calibration. After the nozzle diameter had been recorded, the nozzle was installed in the velocity calibration chamber and the velocity calibration was determined. Additionally, the velocity and loss coefficient (C_v) information was obtained as the intensity calibration was performed.

3.3.1 The Velocity Calibrations

Specific tests were designed in order to generate both the velocity-pressure and loss coefficient pressure relationships. With the nozzle in the calibration chamber, the pressure was increased in 1,000 psi increments from 1,000 psi to 15,000 psi. For each pressure increment, three flow rate measurements were recorded. The repeat measurements ensured accuracy and reproductibility of the data generated. Applying this data to equation [1], the nozzle velocity as a function of nozzle pressure was determined.

$$V_o = Q(0.321)/A \qquad [1]$$

where:

V_o = nozzle velocity (fps)

Q = flow rate (gpm)

A = nozzle orifice area (in^2)

The second relationship developed from the velocity calibration data was the loss coefficient as a function of pressure. The loss coefficient (C_v) is defined by:

$$C_v = \frac{V_o}{V_{th}} \qquad [2]$$

where:

C_v = loss coefficient (nondimension)

V_o = actual nozzle velocity (fps)

V_{th} = theoretical nozzle velocity (fps)

The theoretical velocity is defined as the velocity potential and is dependent on operating pressure. The following equation mathematically defines V_{th}:

$$V_{th} = \sqrt{2 \bullet g \bullet \Delta P \bullet 2.3} \qquad [3]$$

where:

V_{th} = theoretical velocity (fps)

g = gravitational force (ft/sec^2)

ΔP = pressure drop across the nozzle orifice (psi) (5)

The velocities calculated from equation [1] are applied to equation [2], as are the values of V_{th} calculated from equation [3] for each pressure in increment in the profile. The loss coefficient, C_v, as a function of nozzle pressure can be calculated. This nondimensional velocity coefficient is used as a performance indicator for the nozzle. An efficient nozzle will have a high C_v factor and will be constant with respect to pressure.

3.3.2 The Intensity Calibrations

The intensity calibrations were utilized to determine the remaining parameters of interest for each nozzle with the exception of cleaning rate. For these experiments, the test chamber was utilized. Intensity calibrations were performed at a chamber pressure of zero psi (sea level water depth). The nozzle was secured within the test chamber along with a test sample specimen. The sample material utilized for all intensity calibrations was 1/4 inch thick 1100-F aluminum plate, 6 inches square. This material was chosen because the erosion strength was a known quantity. With this equipment installed, the chamber was sealed, flooded and testing initiated.

The intensity calibration measured breakthrough time (B_t), which was used to calculate intensity of erosion. Breakthrough time was defined as the time required for the impinging jet to penetrate the specimen plate. Breakthrough time was measured as a function of nozzle distance for nozzle pressures in the range of 10,000 to 15,000 psi. At a specific pressure, the nozzle distance

(D_n) was varied form 0.25 to 0.75 inches. At each distance setting, three breakthrough times were measured. The additional measurements were made to ensure accuracy and reproductibility. In addition, a check on nozzle performance was made. For each adjustment of the distance setting, a flow rate measurement was made. This information was compared with the velocity calibration and previous measurements in order to ensure consistent nozzle operation. As each breakthrough time measurement was made, the test sample was rotated to a clear position to start the next data point.

The breakthrough time data was applied to the following equation which defines intensity of cavitation erosion:

$$I_e = \frac{i \bullet S_e \bullet (175.3)}{t} \qquad [4]$$

where:

I_e = intensity of erosion (w/m^2)

i = erosion depth (thickness of sample plate) (in)

t = exposure time (breakthrough time measured) (sec)

S_e = erosion strength of the material (psi)

Calculated values of I_e were normally plotted as a function of nozzle pressure and/or distance.

The nozzle power parameter was obtained for each nozzle evaluated. Nozzle power was plotted as a function of nozzle pressure.

Data obtained from both calibration tests were utilized to determine nozzle power from the following equation:

$$HP_m = \frac{Q \quad \Delta P}{1714} \qquad [5]$$

where:

HP_m = measured nozzle power (HP_m)

Q = nozzle flow rate for a given ΔP (gpm)

ΔP = pressure drop across the orifice (psi)

The nozzle power parameter was utilized for optimization and definition of the equipment needs for the field experimentation.

3.3.3 Cleaning Rate Experimentation

With the barnacle fouled sample mounted in the specimen support and the nozzle set in position, the traverse mechanism was utilized to determine cleaning rate. The mechanism was equipped with variable speed motor control. This control allowed the rate at which the sample moved past the nozzle to be set in a range from 0 to 15 in/sec. The other adjustable feature of the apparatus was the nozzle position adjustment. Both nozzle distance and nozzle impingement angle were adjustable. For these experiments, nozzle angle was not varied. The nozzle was set so that the jet impingement angle with the sample plate was 90 degrees. In this manner, all cleaning rate data was obtained as a function of nozzle distance and nozzle pressure.

When all initial test conditions were set, the data was obtained by setting the traverse rate and moving the plate past the nozzle.

After each test run, the cleaned surface area of the sample was measured and recorded. By dividing traverse rate by specimen plate length and multiplying times the area cleaned for the exposure period, a cleaning rate was established.

3.3.4 Water Depth Effect Experimentation

The effect of water depth on the nozzle performance was investigated. These tests were conducted in the pressure chamber used in the intensity calibrations. The procedure was the same with respect to measurements that were made. The major difference in these tests were the particular parameters involved.

Breakthrough time for each nozzle was measured with respect to distance, depth, and pressure. The depth was simulated by controlling the discharge to the chamber which caused the pressure to increase inside the chamber. Each discreet pressure simulated a particular water depth. Pressures were adjusted in order to simulate water depths from 0 to 150 feet.

Two experimental procedures were conducted. The first investigated the effect of depth, holding nozzle distance constant, for three different nozzle pressures. At each depth and pressure setting, three measurements of breakthrough time were made. The second test sequence investigated the distance-depth relationship for one operating nozzle pressure. For each distance and depth combination, three breakthrough time measurements were made.

The data obtained was used to determine intensity of erosion and thereby establish the intensity-depth relationships. The method used to determine I_e was described previously in this report.

3.4 Field Procedures

The field experiments served two separate purposes. The first was to generate data with respect to performance of the technology under field conditions. The second was to demonstrate the technology to cognizant government and industrial personnel. In order to keep complete records and allow the visitors a first hand observation of CONCAVER technology in operation, a video tape recording system and underwater camera were used to record the complete operation.

The actual field operations were defined and scheduled in a proposed agenda which was distributed to each visitor. In addition, a proposed activities sheet which described in detail all the activities undertaken was distributed.

Six tasks were outlined to be accomplished over the two day demonstration period. Those tasks included:

1. A demonstration of the ability to control the gun in single hand operation in two configurations.
2. A demonstration of the single pass cleaning of each nozzle design.
3. A demonstration of the ability to clean weld joints to bright metal.
4. A demonstration of the ability to function with the equipment in a limited access situation.
5. A demonstration of the ability to clean at several different water depths within the depth limitations of the test sight.

6. The establishment of actual cleaning rates for the field condition operations.

For each task, a briefing and debriefing of the divers were conducted. Each time that a diving team entered the water, one and only one specific task was undertaken (6,7). This procedure was established to minimize the chance for confusion of instructions for any operation.

The video tape records constituted 1/3 of the visual documentation; 16mm movie film and 35mm slide film were also used to record both the above water and underwater portions of the experimentation.

The field operation took place at the outermost channel light structure at the mouth of the Miami River. Figure 10 is a photograph of the structure. It was a four-pile construction platform with a truss work connecting the four pilings. The structure stands approximately 40 feet above the water surface and stands in water approximately 30 feet deep. The light structure is located about three miles offshore.

A work boat was contracted by the U.S.G.S. to provide a work platform that would provide easy access to the light structure as well as a stable diving platform. Figure 11 is a photograph of the vessel which served as the work platform for the field testing and demonstration. The vessel was 112 feet long and 32 feet abeam with a flat bottom. This hull configuration provided a very comfortable and stable working platform.

4.0 EXPERIMENTAL RESULTS AND DISCUSSIONS

4.1 Laboratory Experimental Results

4.1.1 Nozzle Evaluations

The examination of the ASTM standard orifice nozzle (Phase I) had indicated that the size and shape of the cavitation bubble envelope was not satisfactory for cleaning. The maximum width cleaned with this nozzle was 1/8 inch. The area of surface impingement restricted the cavitation cleaning to a very narrow surface. What was needed was a nozzle design which would change the configuration of the cavitation envelope so that the jet impingement was distributed over a wider area of the surface to be cleaned.

Several attempts were made before a successful nozzle was developed. This new design was referred to as a fan jet nozzle. Figure 12 is an artist's illustration of the difference of the cavitation envelope between the standard orifice and the fan jet designs. Nozzle calibration data was generated for the fan nozzle so that a direct comparison of the two designs was possible. The objective of these design efforts was to obtain a better cleaning nozzle which operates at nearly the same power requirements as the standard orifice design evaluated in Phase I.

When the velocity calibration of the fan jet was complete, the velocity and loss coefficient were plotted with respect to pressure. Figure 13 is the velocity profile with respect to pressure obtained from calibration. Analysis of this data indicated the velocity profile was comparable to previous nozzle calibrations. The maximum velocity obtained was 1,250 fps at 15,000 psi. This velocity was higher than obtained for the standard nozzles but not significantly. The loss coefficient for the fan jet was also plotted. Figure 14 illustrates the plot of that data. The C_v data is constant with respect to pressure over the range of importance. In addition, the data indicated that this design has a rather high loss coefficient value. The design was an efficient one, as well as covering a wider area.

The velocity data was then plotted with the data for the 0.031 inch diameter nozzle which was found to be most efficient in Phase I. Figure 15 is the graph of the velocity data for the two nozzle designs. The velocity for the fan nozzle was higher at pressures below 11,000 psi. Above that pressure the velocity profiles for the two designs begin to converge. This condition was apparent in the loss coefficient data as well. Figure 16 is the graphic representation of the loss coefficient comparison. The data also illustrated that the fan jet design was approximately ten percent more efficient than the standard orifice nozzle.

The final evaluation criteria to be met was the power required for each nozzle. To establish that relationship, the nozzle power for the fan jet was calculated and plotted with the power figures for the standard orifice. In addition, the flow rate as a function of pressure was also plotted. Although flow rate and power were related, the decision was made to indicate the precise flow rate comparison. Figure 17 is the flow rate comparison. As was the case with the velocity data, a slightly higher flow rate was obtained from the fan jet below 11,000 psi pressure. This additional flow was beneficial, however, because higher velocities were developed. Figure 18 is the power comparison for the amount of power produced at the nozzle. For nozzle pressures below 11,000 psi, the horsepower produced at the nozzle was higher by approximately 13 percent. The change in nozzle design was delivering a modified cavitation envelope and at slightly improved performance figures. The next step was to demonstrate the increased cleaning capability.

4.1.2 Cleaning Rate Evaluations

The nozzle parameter directly related to ability to perform a cleaning task was intensity of cavitation erosion. Following the procedure described previously, intensity of erosion data was gathered for the fan jet nozzle. This data was obtained for nozzle pressures ranging from 8,000 to 15,000 psi and for nozzle distances ranging from 0.1 to 0.5 inches.

For each pressure or distance set, an intensity value was obtained. Figure 19 illustrates graphically the intensity of erosion as a function of pressure for 0.5 inch nozzle distance. Shown was the continued increasing intensity of erosion with respect to pressure. This relationship was representative of the data obtained at each nozzle distance. More important to the utilization of the nozzle was the relationship of intensity of erosion with respect to nozzle distance for any given pressure. Figure 20 is the curve of intensity as a function of distance for the fan jet at 14,000 psi nozzle pressure. The maximum intensity obtained was 10,954 w/m^2 which occurred at a nozzle distance of 0.2 inch.

The evaluation process necessitated determining I_e values in this manner in order to establish intensity comparisons. For essentially the same breakthrough times, the amount of material eroded from the aluminum plate was increased using the fan jet nozzle design. The 0.031 inch diameter standard nozzle eroded a circular area approximately 1/8 inch in diameter with a length the thickness of the plate. The fan jet, operating at the same pressure, eroded an area of rectangular shape and the thickness of the plate. The volumes removed were:

Standard Nozzle = 1.534×10^{-3} in^3

Fan Jet Nozzle = 8.777×10^{-3} in^3

This indicated an improvement factor of 5.7. A similar improvement was expected for the cleaning rate.

In order to compare this data with the standard orifice nozzle, the intensity curves for both nozzles were plotted together. Figure 21 is the comparison data of I_e as a function of nozzle distance at 10,000 psi nozzle pressure. The detrimental affect of spreading the cavitation envelope out can be observed in Figure 21. The standard orifice nozzle maintained an intensity of over 1,000 w/m^2 for a range of nozzle distance from 0.2 to 1.2 inches. The restriction of nozzle distance was not severe. For the fan jet, the intensity maximum was comparable to the standard orifice design. With respect to distance, the intensity of the fan jet dissipated rapidly.

The fan intensity dropped below 1,000 w/m^2 at a distance of 0.4 inches.

With this data as a guide and the knowledge that the field equipment pressure limit was 10,000 psi, laboratory cleaning rate tests were conducted with the fan jet nozzle.

The tests were conducted at 0.25 inch nozzle distance to start. The data obtained at this point was so encouraging that attempts were made to clean at greater distances. Figure 22 graphically represents the laboratory cleaning rates obtained. The data was taken again to insure no errors and was confirmed. As indicated in Figure 22, the cleaning rates increased from 0.25 to 1.0 inch nozzle distance. However, in both tests, the cleaning was not effective at all beyond a 1.0 inch distance. The maximum width cleaning in these tests was 1.25 inches. This width was ten times that cleaned by the standard orifice nozzle. The actual cleaning rates were six times greater than those reported in Phase I. The maximum cleaning rate for the removal of fouling and paint coating to bright metal was 1.56 ft^2/min or 94 ft^2/hr.

Although the intensity numbers were not high above 0.5 inch nozzle distance, the cleaning rate tests did indicate the value remained above 450 w/m^2 out to a nozzle distance of 1 inch. Between 1 and 1.25 inches the intensity value dropped below 450 w/m^2. This intensity value was determined to be the barnacle threshold intensity and as long as I_e remained above that number cleaning would occur. The test data illustrated in Figure 22 attests to this fact.

Cleaning did occur at a nozzle distance of 1 inch but did not occur at a distance of 1.25 inches. The increased rate at 1 inch resulted from the wider coverage area of the fan.

4.1.3 Water Depth Evaluations

The final portion of the laboratory experimentation dealt with the effect on intensity of cavitation erosion of water depth. Initial tests were conducted with the standard orifice nozzle. The breakthrough time of the nozzle was measured as a function of depth. These tests were accomplished in the same manner described previously but the nozzle distance was constant and the chamber pressure was varied. Figure 23 shows the depth range investigated was from 0 to 115 feet. From the evaluation of Figure 23, below 11,000 psi nozzle depth had a beneficial affect up to 40 feet. Between 40 and 115 feet the increasing depth began and continued to have a detrimental effect. As the operating pressure was increased, the depth at which the adverse effect initiated was shifted from 40 feet to 90 feet. The advantage was realized at the higher pressures.

The intensity of erosion data and breakthrough time data could be compared without actually determining I_e. This was possible because breakthrough time and intensity of erosion are inversely proportional functions. As breakthrough time decreased the intensity of erosion increased.

The results of the initial tests were an indication of a trend but were less than optimum. The nozzle distance optimum with respect to pressure would change with increased or decreased water depth. One nozzle pressure (10,000 psi) was selected for further evaluation. A second set of data was taken with the standard orifice nozzle. Figure 24 illustrates what occurs if the nozzle distance were to change with depth in order to obtain the optimum breakthrough time. The severity of the adverse effect was nullified by adjusting nozzle distance so that the optimum breakthrough conditions were maintained. Also, this data was conducted to depths of 150 feet. Even to a depth of 150 feet, an advantage was realized using this optimization method.

The next test sequence was to test the fan jet nozzle under similar conditions in order to compare the depth effect on the two designs. The same depth range was tested. The fan jet nozzle was tested at 10,000 psi nozzle pressure for nozzle distances of 1/8 and 1/4 inches. Figure 25 compares the intensity of erosion for the standard orifice nozzle at 1/4 and 3/8 inch nozzle distance with the fan jet at 1/8 and 1/4 inch.

A detailed analysis of this data indicated that depth had the same general effect on both nozzles. The major difference was the nozzle distance at which the effect occurred. The straight orifice nozzle was still demonstrating an ability to maintain a higher intensity over a greater distance. The indication from the data was that an improvement in intensity would be obtained in water depths of 50 feet or less. This data compared well with the initial depth data at 10,000 psi nozzle pressure. That data and the data on Figure 25 both illustrated that 10,000 psi was a reasonable operating pressure for shallow water field conditions. With these findings and accomplishments as encouragement, experimentation moved from the laboratory to field conditions.

4.2 Field Experimental Results

Certain unique questions were to be addressed during the field evaluations. These questions were related to overall performance and safety functions of the equipment which could not be simulated in the laboratory. The items of specific interest were:

1. Could the force of the nozzle system be handled with one hand for extended periods without the diver becoming fatigued?
2. Would the fouling being removed cause a turbidity increase and impair the diver's visibility causing delays?
3. Would the noise generated by the cavitating water jet in any way cause discomfort for the diving personnel?

The answers to these questions were obtained from discussions with the divers and observations of the diving activities through the use of underwater video equipment. The instant replay of the video tape allowed the diver to make comments while viewing the activity.

The following information constitutes a task by task summary of the observations and subjective information obtained in the field. After these comments, the objective field data will be addressed.

Task I - Single Hand Operation

Thrust calculations for the equipment indicated the maximum thrust would be less than 7 pounds at 10,000 psi. Two configurations were tested in order to establish which operation was the least taxing on the diver. The tests were conducted working with the gun alone or with the quick connect shoulder stock. The diver reported no difficulty working against the thrust in either configuration. However, he expressed a preference for the configuration without the shoulder stock, because it allowed more flexibility and easier control of the nozzle distance and thrust.

At the conclusion of the first test period, the divers reported the following:

1. No fatigue experienced from use of the gun single-handed;
2. For the area cleaned, turbidity did not hamper the operations in any way;
3. For the diver/operator the noise was noticeable but not objectionable. The diver/camera operator reported that at distances greater than five feet the noise was no problem.

Task II - Single Pass Cleaning Comparison

This task was intended to show, by way of video tape, the difference of the width of the clean path for the two nozzle designs. The standard nozzle was tested first then the fan jet nozzle. Both the gun and operator and the video camera operator reported a much wider cleaning area with the fan jet nozzle. The standard orifice nozzle had cleaned an area approximately 0.75 to 1 inch wide as compared to an area of approximately 2.5 to 3 inches wide with the fan jet nozzle. As a special task, a section of scrap pipe from the bottom was cleaned in place and raised on deck for inspection. Figure 26 is that pipe section just after it was placed on deck.

This was the only period of the field testing where the turbidity caused delays but at no time was this considered to be a major problem, because nominally 10 to 20 seconds were required before he was able to proceed.

Task III - Cleaning a Weld Joint Area

This task was performed twice in order to demonstrate the differences of the nozzle designs. Because this type of cleaning was restricted to an isolated area, both nozzle designs were capable of accomplishing the task satisfactorily. The fan nozzle appeared to clean the weld faster and got the entire area clean without backtracking. After the nozzle had passed, it was possible to see the bright metal of the weld and the wave of the weld bead. Another advantage of the fan jet was its ability to clean the complete weld area and the boundary metal at the same time. This ability would allow for more complete and accurate inspection of the weld joints.

Task IV - Cleaning in Limited Access

A portion of this task was to demonstrate the ability to clean in limited access with configuration changes. This was eliminated as a result of the diver's expressed preference not to change the configuration. To demonstrate limited access on this structure, another weld area at the base of the structure was cleaned. In order to clean the complete joint, access to the underside of the joint was required. The diver was able to reach under with the gun and completely clean the joint. The diver reported no difficulty in controlling the gun in this manner.

Task V - Water Depth Effect

The demonstration of the nozzle functions with respect to water depth was accomplished at two different times. Laboratory data had indicated that water depths of 50 feet or less would have no detrimental effect on cleaning. The subsurface portion of the platform was in approximately 30 feet of water. The single pass cleaning from base to water surface served as one demonstration. In this test, cleaning rate was maintained for both nozzles throughout the available depth range with no interference of cleaning.

The second activity which illustrated depth influence was the cleaning of the two horizontal brace work sections of the platform. One of the brace sections was located about six inches below the surface. The other brace section was located at a depth of approximately 30 feet nominally 10 inches off of the bottom. Both of these brace sections were cleaned at different times over the course of the field testing at no noticeable difference in cleaning rate or ability.

The results mentioned above are all of the subjective observations made during the operations. The information from Task VI constitutes the objective data gathered during these operations.

Task VI - Cleaning Rate Determinations

Data was obtained in order to compare laboratory and field condition cleaning rates. Two conditions were evaluated: cleaning to remove only the marine growth; and cleaning to remove the marine growth and coal tar protective coating. The data and rates for each test are shown below. For the bright metal cleaning test, a section of discarded pipe was used so that the tower would not be affected adversely.

Bright Metal Cleaning

Dimensions of Areas Cleaned

15" x 13"

12" x 14" 363 in^2

Total Time 2.6 minutes

Cleaning Rate = 363 in^2/2.6 min.

= 139.62 in^2/min.

≈ 60 ft^2/hr.

Marine Fouling Removal

Dimensions of Area Cleaned

180" x 10.5" = 1890 in^2

Total Time 2.0 minutes

Cleaning Rate = 1890/2 in^2/min.

= 945 in^2/min.

≈ 400 ft^2/hr.

One additional test sequence of cleaning ability was conducted. Interest in the ability of the gun and nozzle to clean propellers had been expressed by observers. To demonstrate this ability, the propeller on the vessel was cleaned. The propeller was a four-bladed 42 inch diameter propeller. The fouling on the prop was not extensive but the fouling on the shaft support struts was extensive. Three face surfaces and two back surfaces and some of the struts were cleaned in a total time of 20 minutes. Approximately 15 minutes were spent cleaning the propeller. Therefore, 63 percent of the propeller surface was cleaned in 15 minutes. The complete surface could be cleaned in nominally 30 minutes. This rate would translate to: 6 hours to clean a 12 foot diameter propeller. This rate was considered to be very good. The propeller was cleaned to bright metal. Both barnacles and the calcareous platelets were removed in the single operation.

A comparison of the overall performance of the field tests with the laboratory data indicated a slight reduction over the laboratory predicted rates. The reductions were the result of several contributing factors. The diver does not maintain the optimum nozzle distance and was inclined to retrace his steps to insure complete cleaning to perfection.

Laboratory tests had been conducted using single length of flex-lance and a nominal pressure drop was noted. In the field tests, three lengths of the hose were coupled together. The hose was stainless steel braided with a teflon interior lining. The interior diameter of the hose was 0.25 inches. However, the end fittings on the hose were 1/8 male pipe which have an actual interior diameter of 0.15 inches. This coupling seemed to compound the pressure loss in the hose. The resultant loss was nominally 1,500 psi. As a result, the gun was functioning at less than optimum pressure conditions. The combinations of those factors mentioned above have been established as cause for the reduction in cleaning rates from the field experiments.

4.3 Anticipated Field Equipment Modifications

During the course of the field experimentation, certain operations indicated the need for future modifications of equipment. These modifications were realized as methods of improving system performance, improving operating conditions or improving system/personnel safety. The following items detail the anticipated modification to be considered as the CONCAVER system moves into its next generation:

1. The noise discomfort to the diver must be alleviated. This condition possesses problems in that a diver must not plug his ears. The differential pressure between inner and outer ear can result in ruptured eardrums. Several methods will be evaluated in order to solve this problem. One method to be considered is the use of pressure compensated ear muffs which were originally manufactured for divers that had problems equalizing the pressure in their ears under normal conditions.

Another method which will be evaluated as a solution to this problem is the purchase and use of a helmet type diving mask assembly. This type diving mask completely encloses the diver's head within a pressurized helmet. These masks would provide relief of the noise but are more cumbersome to use. In addition, the wet suit must be modified to seal the helmet.

2. The supply hose should be modified in order to reduce the pressure losses in the hose. This change is required to maintain system operation at the optimum operating pressure. A pressure loss of approximately 1,500 psi was experienced with the supply system used. This loss can be eliminated by reducing the number of sections of 0.25 inch internal diameter (ID) hose sections in the supply line.

   Each 0.25 inch ID hose section coupling placed a restriction of 0.15 inch ID in the line. If one section of 0.25 inch ID hose is used, the flexibility of the system will be maintained and the majority of the restrictions can be removed. The additional lengths of small diameter hose will be replaced with 0.50 inch ID high pressure hose which cause minimal pressure losses.

   Two other modifications to the supply hose assembly will be incorporated in the interest of personnel safety. The hose sections will incorporate a tether line which will prevent injury which may result if a coupling_separates or a hose ruptures. Also, the on-deck hoses will be enclosed in a rupture shield. This device will eliminate the possibility of injury to personnel should the hose above water rupture. These modifications to the high pressure line will prevent injury and enhance the cleaning rates. Cleaning rates will improve as the system operation returns to optimum pressure rather than operating at reduced pressure levels.

3. The ability to maintain the optimum standoff distance was one operational situation which reduced the system performance. A slight modification of the nozzling assembly will enable the optimum condition to be maintained during operation. As a portion of the nozzle assembly, a standoff arm should be installed. This arm would be set so that the nozzle is at optimum standoff distance when the arm is in contact with the surface being cleaned. To maintain proper operating condition, the diver would move the gun into the surface and hold the arm in contact with the surface as the cleaning progresses. This modification will improve the cleaning rates and overall performance of the system.

4. The gun requires several modifications in order to provide better diver safety. Some of these modifications are already being evaluated and incorporated. These modifications are necessary as a result of observed structural

deformation occurring in the gun as a result of the high pressure pulsations.

The first modification is the replacement of the "O" ring type seals at the high pressure interfaces with "C" seals. These seals are designed to open and close with pressure pulsations and maintain the seal where "O" ring seals are not. Another protective measure is to sleeve the interface area with a protective collar. Both of these changes are being evaluated at this time.

In addition to reduce the deformations which are occurring, two or three potential changes are being considered. One modification is to increase the size of the bolts holding the handle in place to 1/4-28 UNF-2A. This change would make the joint area more rigid and less deformation would occur. Another modification being evaluated is moving the water feed connection so that water does not pass through the handle. This would eliminate one high pressure seal requirement and eliminate the need to increase the screw sizes. However, this modification would make the unit less convenient to work with.

As well as effort to modify the existing handgun, design effort should be initiated to design a second generation unit which incorporates these best modifications and upgrades the handgun from a human engineering standpoint.

The design should attempt to further reduce the weight of the unit, make the trigger more comfortable to hold, as well as incorporate the modification to improve safety. The trigger assembly should also incorporate a lock open feature so that the trigger locks open when released. The lock must then be removed before the trigger can be pulled again. All of these modifications in design will make the second generation handgun safer and more comfortable to use.

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The successful completion of the laboratory and field experiments for this research program has contributed data and information upon which the following conclusions are based:

Laboratory Experimentation:

1. The change in the cavitation envelope as a result of design changes did not adversely effect the nozzle parameters of; nozzle pressure; nozzle velocity; nozzle flow rate; loss coefficient or nozzle horsepower.
2. Design changes did have an effect upon the intensity of erosion versus nozzle distance. An apparant reduction in nozzle standoff distance was suffered in order to increase cleaning rate.
3. The maximum intensity of erosion obtained for the fan jet nozzle design was approximately 10,000 w/m^2 versus 12,000 w/m^2 for the standard orifice nozzle.
4. At 10,000 psi operating nozzle pressure, the fan nozzle developed approximately 14 hp. This is an increase of 13 percent over the equivalent power figure for the standard nozzle.
5. The width of area cleaned with the fan jet was ten times greater than the standard nozzle. The standard nozzle cleans an area of maximum width of 0.125 inches versus a width of 1.25 inches for the fan jet.

6. Cleaning rate to bright metal for the fan jet nozzle was 1.56 ft^2/min. This rate was six times greater than previous nozzle rate data.
7. The increased cleaning rates for the fan jet nozzle were obtained for operating pressures 4,000 psi lower than those used for the standard nozzle design.
8. The cleaning rates obtained are not adversely affected by increasing water depth up to a depth of 50 feet.

Field Experimentation:

9. A force of less than seven pounds is exerted by the gun on the diver. This force can be handled for periods of up to one hour without the diver being overly fatigued.
10. Turbidity is not a major problem. Any clouding of the work area will dissipate within 30 seconds.
11. The cavitation noise does become irritating to the diver if he is exposed to those conditions for longer than 45 minutes or works within a confined space.
12. A system for cleaning can be made available with 25 hp input power as its maximum value.
13. Cleaning rates down to a bright metal surface were obtained 1 ft^2/min. or 60 ft^2/hr.
14. The operating pressure of the gun was reduced by 1,500 psi as the result of using three sections of stainless steel flexible hosing totaling 150 feet.

15. This system can be utilized to clean propellers at an estimated rate of one 12 foot diameter propeller every 6 hours.

5.2 Recommendations

The data from the laboratory and field tests have formed the basis for the following recommendations that cover all phases of operation from procedural changes to operational safety:

1. The fan jet nozzle design be utilized as the nozzle for cleaning offshore structures based on its increased cleaning capability.
2. Additional nozzle design research be conducted in order to develop a nozzle which will perform as well as the fan jet nozzle at water depths from 50 to 200 feet.
3. The hose system supplying the gun be modified in order to reduce the pressure losses. One 25 foot section of the 0.25 inch ID flexible hose can be used for diver mobility and flexibility but, in order to reduce the pressure losses, the majority of the supply hose should be high pressure large diameter hose. This hose has 0.5 inch ID with 0.5 inch connectors and the only flow restriction would occur at the reduction from this size to the smaller flex-hose.
4. For prolonged use of the cavitation system underwater, special protection to reduce noise discomfort for the diver should be provided. Pressure equalizing ear muffs and/or full head covering masks should be evaluated to determine the best method of relieving this discomfort.

5. The on-deck supply hose reel assembly should be covered to prevent injury which might occur from the failure of the reeled hose.
6. The pump should be equipped with an automatically adjustable flow control system which will only allow the design nozzle flow to be delivered to the gun and automatically bypass excess flow to waste or shut off the system.
7. The supply hose sections should be equipped with a tethering line to prevent injury if a section coupling separates or a hose ruptures. This type of failure can cause a whiplash effect to occur at the rupture and a tether will eliminate that occurrence.
8. The nozzle operating pressure is to be maintained at 10,000 psi. This pressure is the operating limit of most commercially available high pressure pumps. Although the flow from these pumps exceeds the gun operating limit, if each gun is equipped with automatic flow control, as many as three guns could be operated with one commercial pump. The cleaning rates obtained at 10,000 psi pressure were satisfactory to excellent. Increasing the operating pressure would increase the power required. The tradeoff is not justified by the research data.
9. The pump operator should become a link in the diver communication system. This action will eliminate any possibility of improper communication being transmitted between surface and subsurface operators.

10. Experiments need to be conducted to evaluate methods of extending the range of nozzle distance for which the intensity of cavitation erosion is high. A major improvement in cleaning rate can be achieved if the nozzle distance can be increased to four or five inches.
11. Two modifications to the handgun should be made as a result of the field tests. The first is the increase of the bolts holding the handgun handle on to 1/4 - 28 UNF-2A. The second is tó replace the "O" ring seals at the high pressure interfaces with "C" seals. These modifications will provide better safety protection to the diver with respect to structural deformation as a result of the high pressure pulsations.

These design modifications and other safety related changes have been made. In addition, the area of the high pressure seal at the barrel was sleeved with a protective shield which acts as additional protection against high pressure seal failure. As this gun was the initial prototype, human engineering and additional safety considerations are being incorporated in the second generation handgun design.

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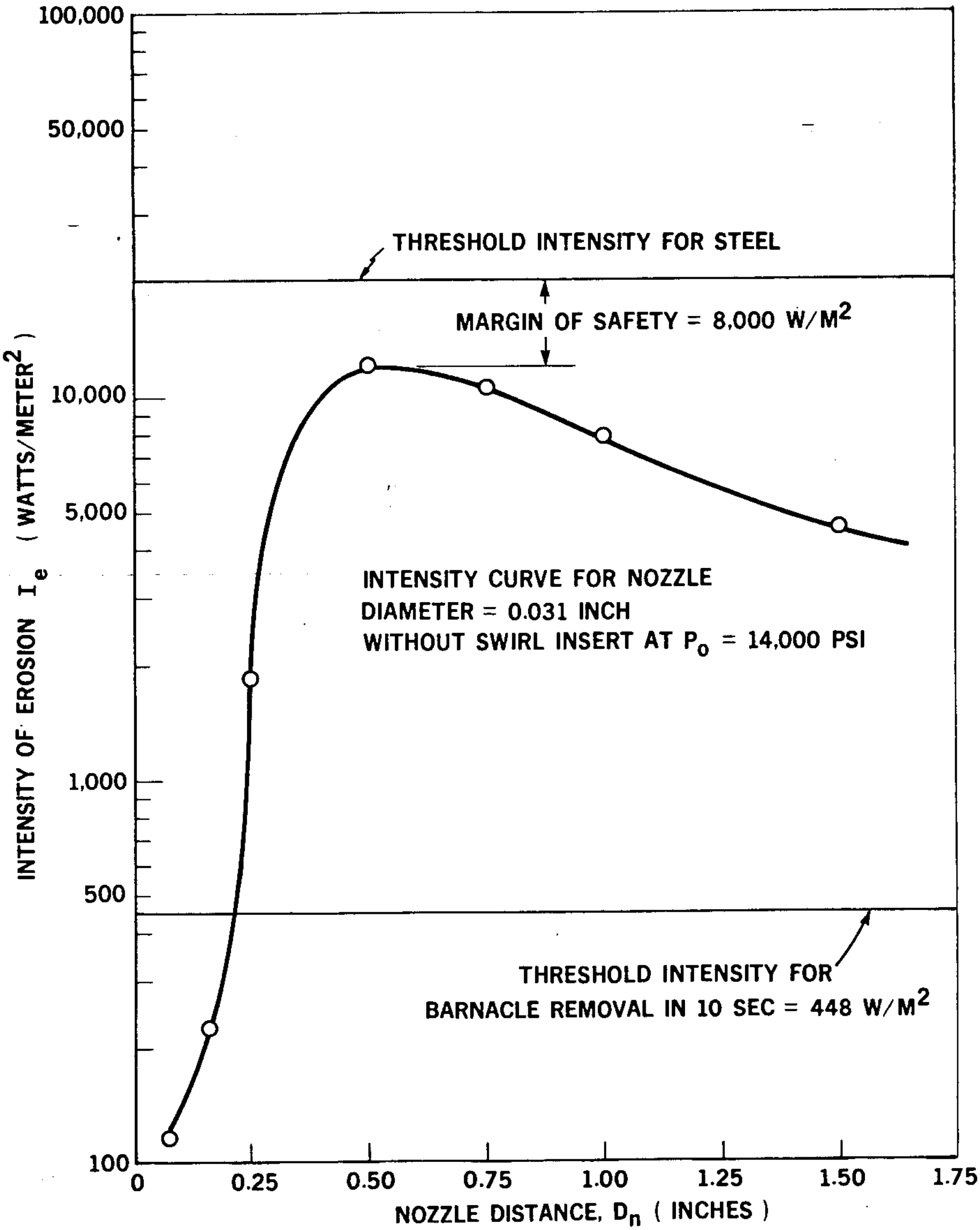

FIGURE 1 THRESHOLD INTENSITY FOR BARNACLE REMOVAL FROM PLATFORM STRUCTURE

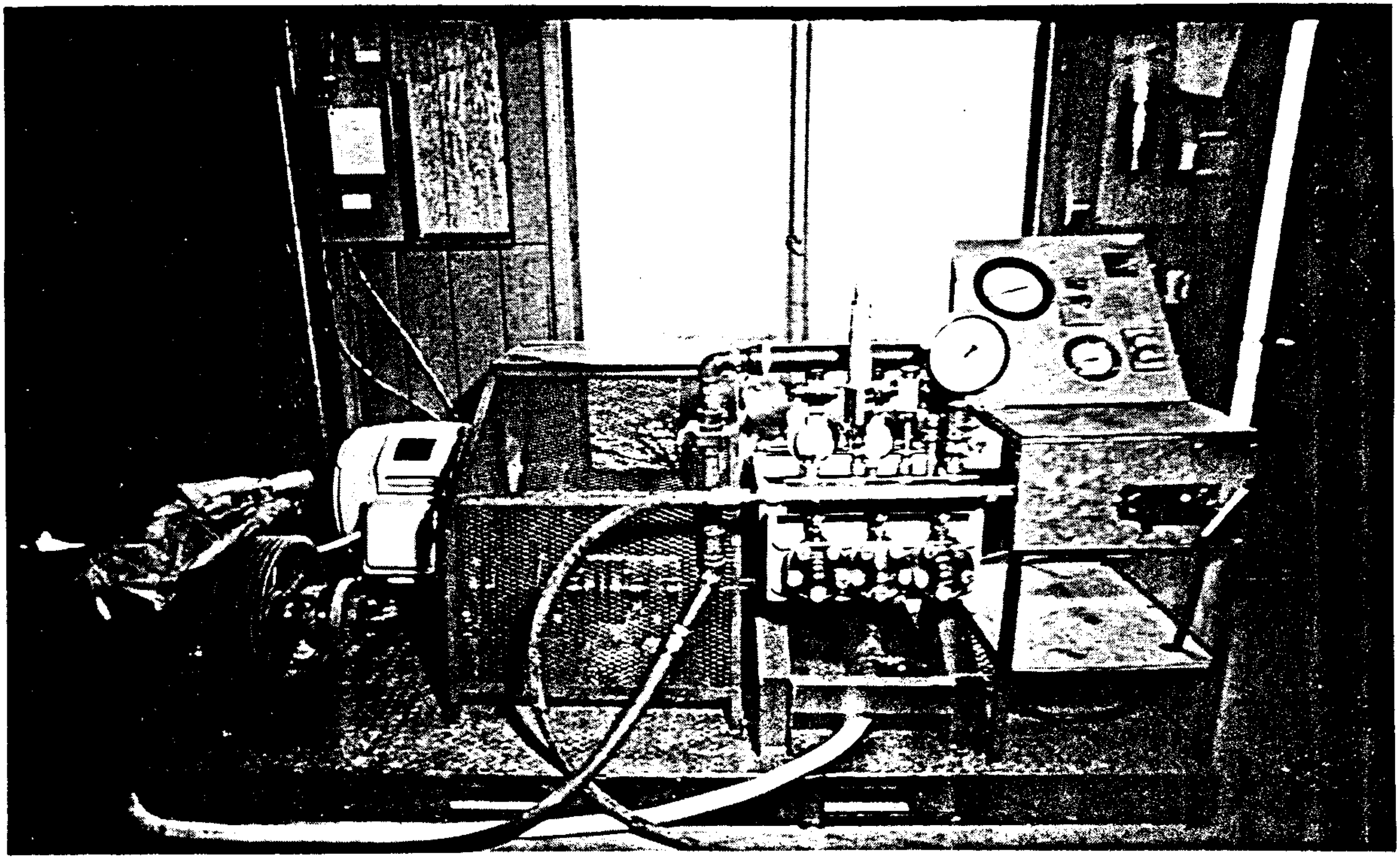

FIGURE 2 PHOTOGRAPHIC REPRESENTATION OF THE LABORATORY PUMPING SYSTEM RATED AT 15,000 PSI AND 4 GPM

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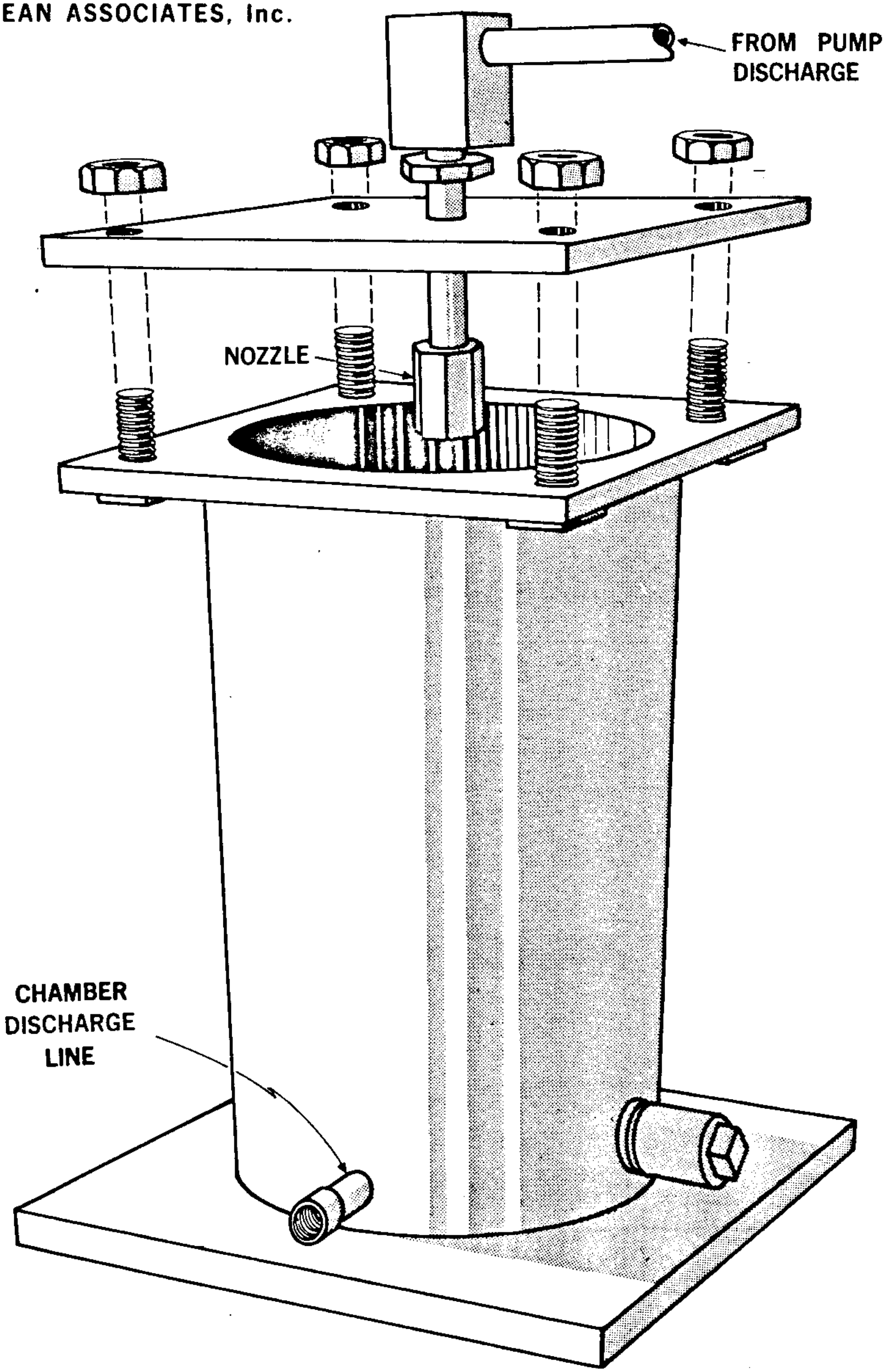

FIGURE 3 DESIGN CONCEPT DRAWING OF THE VELOCITY CALIBRATION CHAMBER

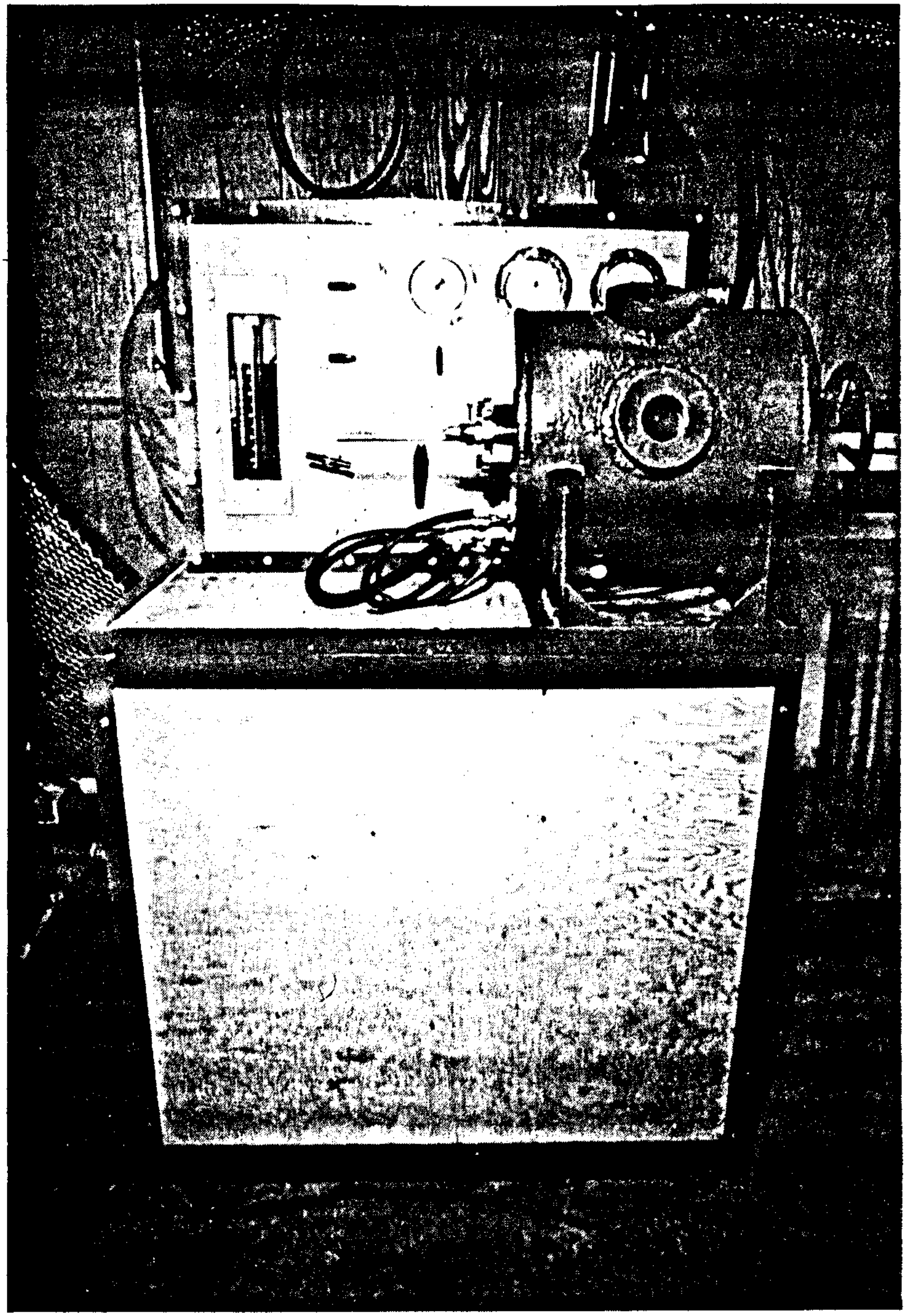

FIGURE 4 PHOTOGRAPHIC REPRESENTATION OF THE INTENSITY CALIBRATION PRESSURE CHAMBER WITH CONTROL PANEL

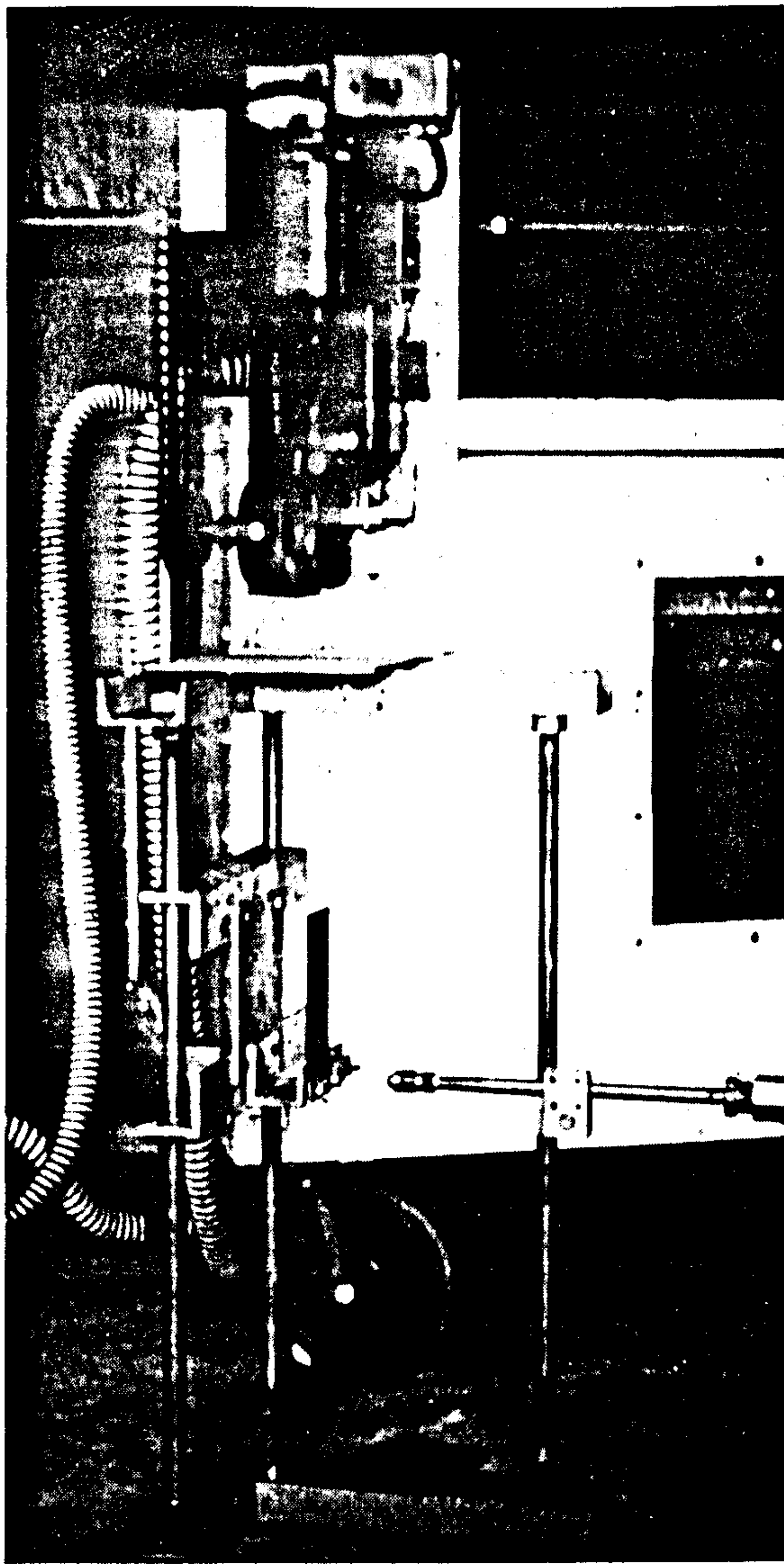

FIGURE 5 PHOTOGRAPHIC REPRESENTATION OF THE TRAVERSE MECHANISM UTILIZED IN CLEANING RATE EXPERIMENTS

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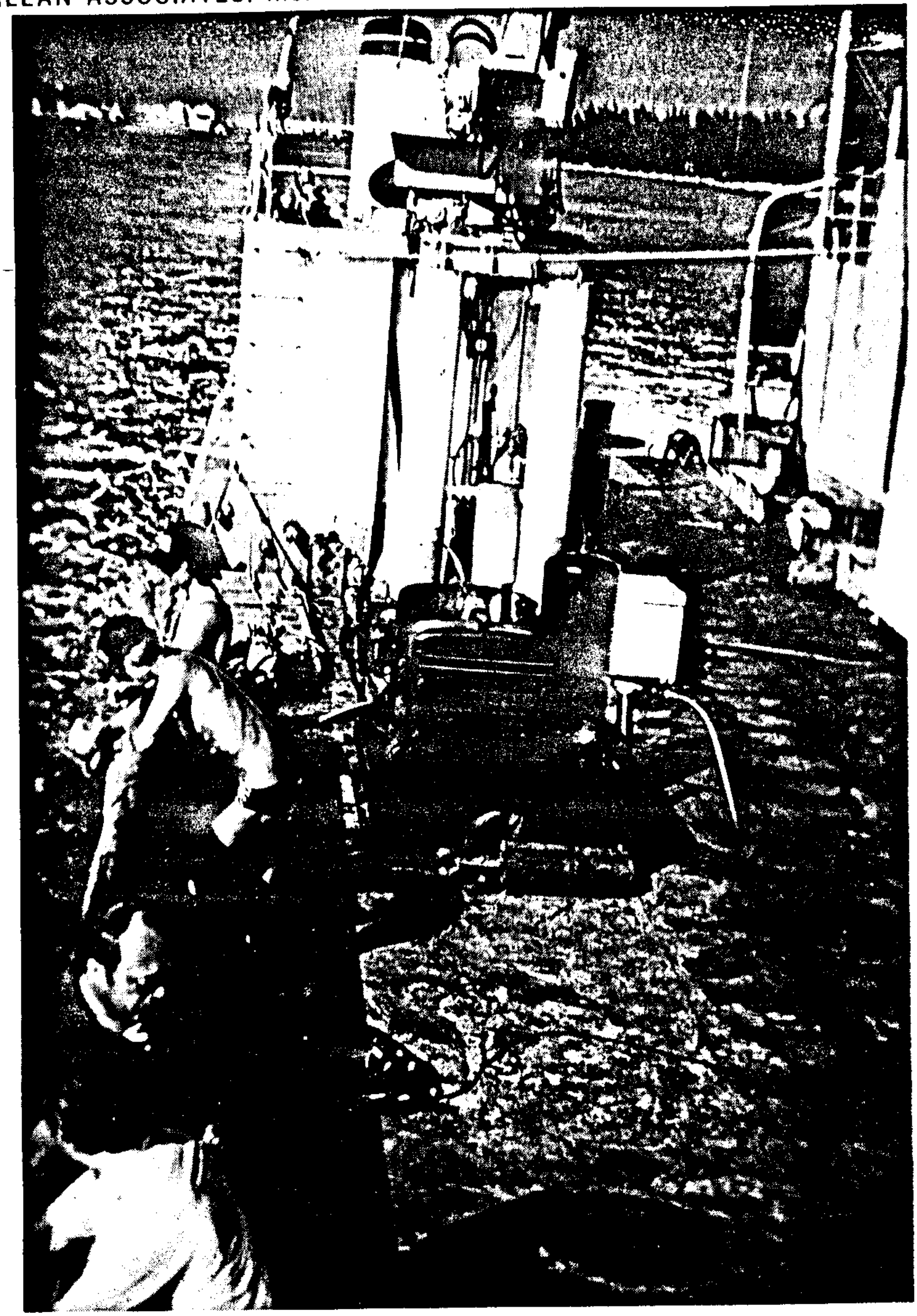


FIGURE 6 PHOTOGRAPH OF THE FIELD EXPERIMENT PUMPING SYSTEM INSTALLED ON THE VESSEL.

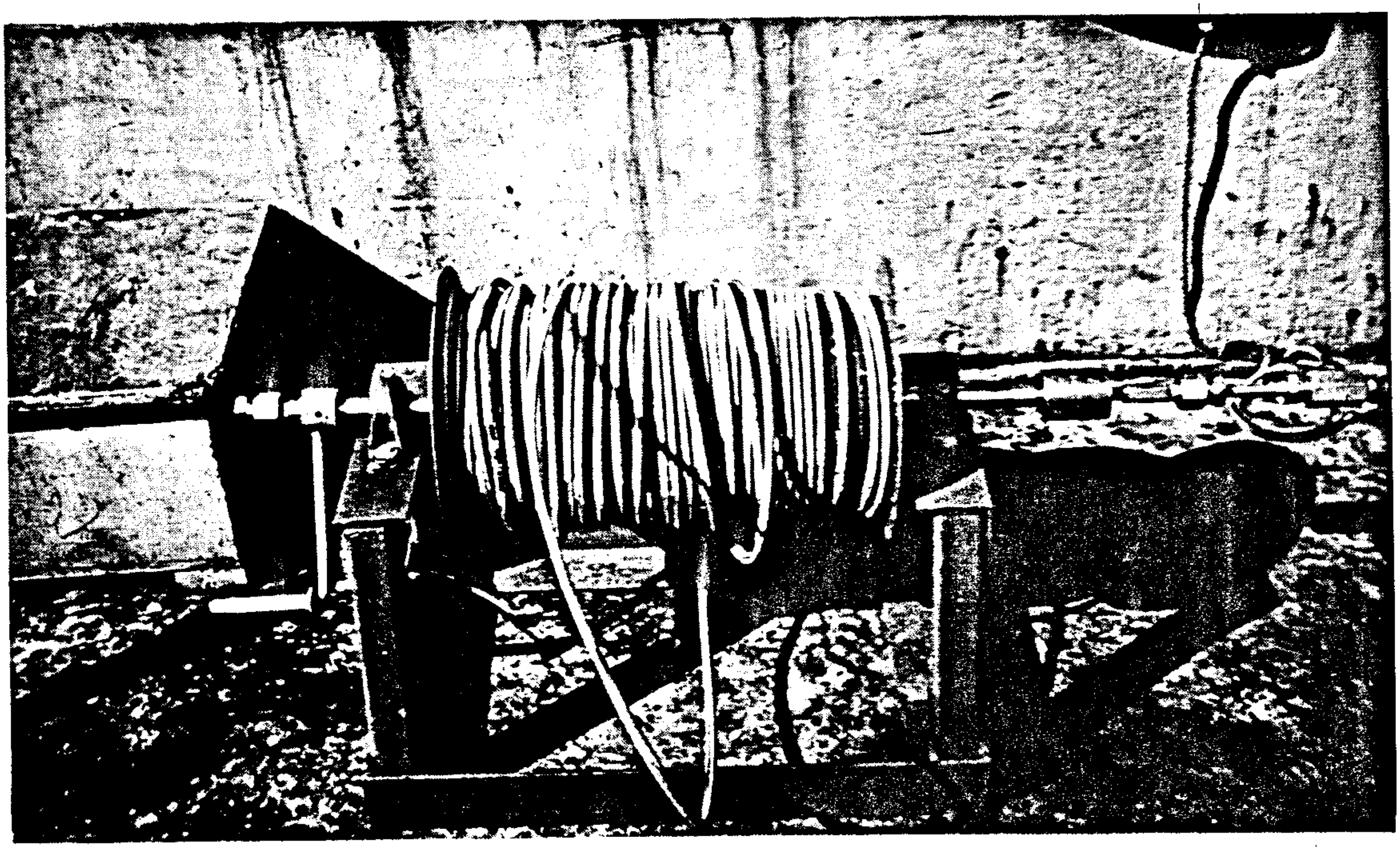


FIGURE 7 PHOTOGRAPH OF THE HOSE REEL ASSEMBLY AND ROTARY SEAL

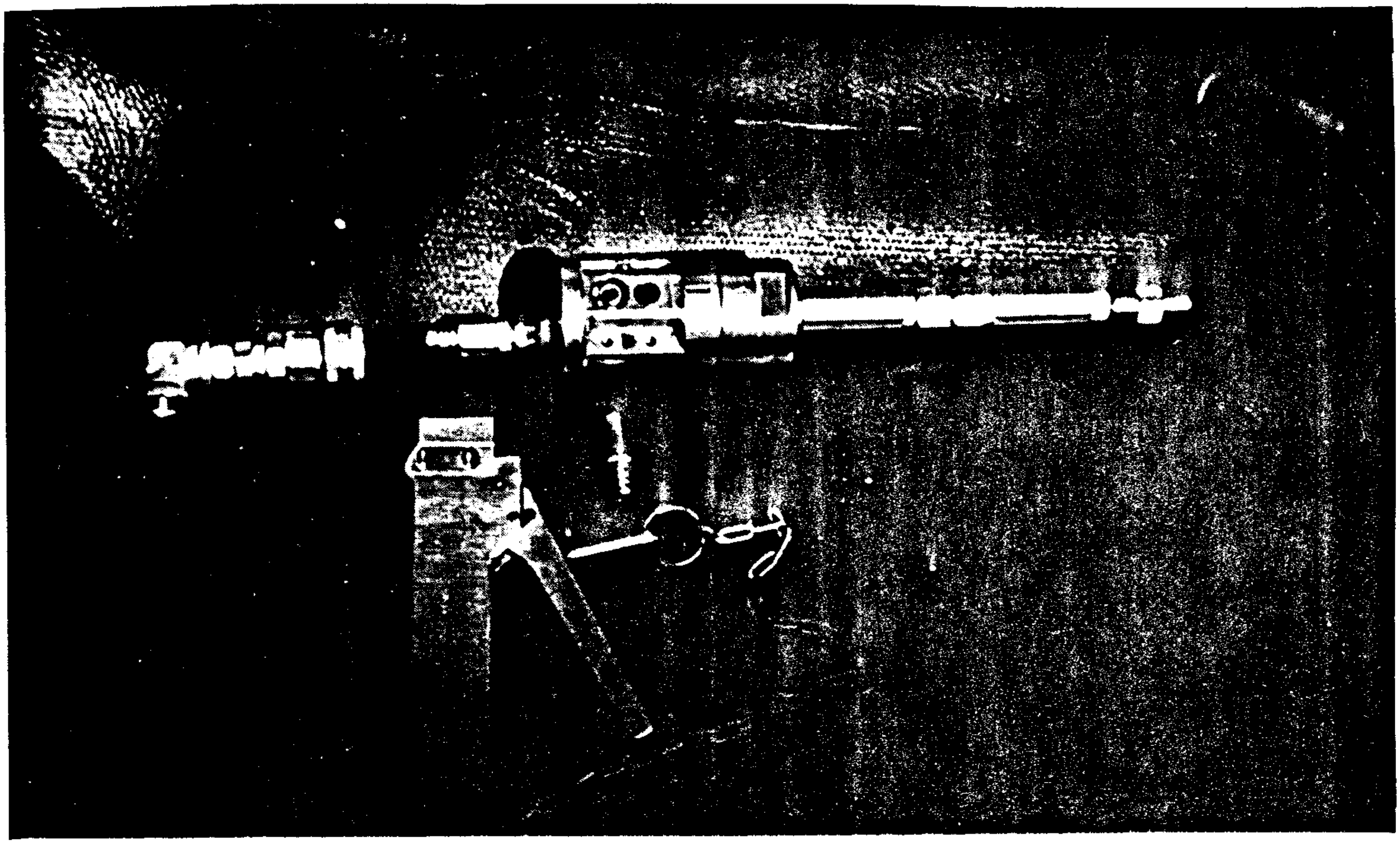


FIGURE 8 PHOTOGRAPH OF THE GUN ASSEMBLY EXPLODED VIEW ILLUSTRATING ALL OF THE COMPONENT PARTS

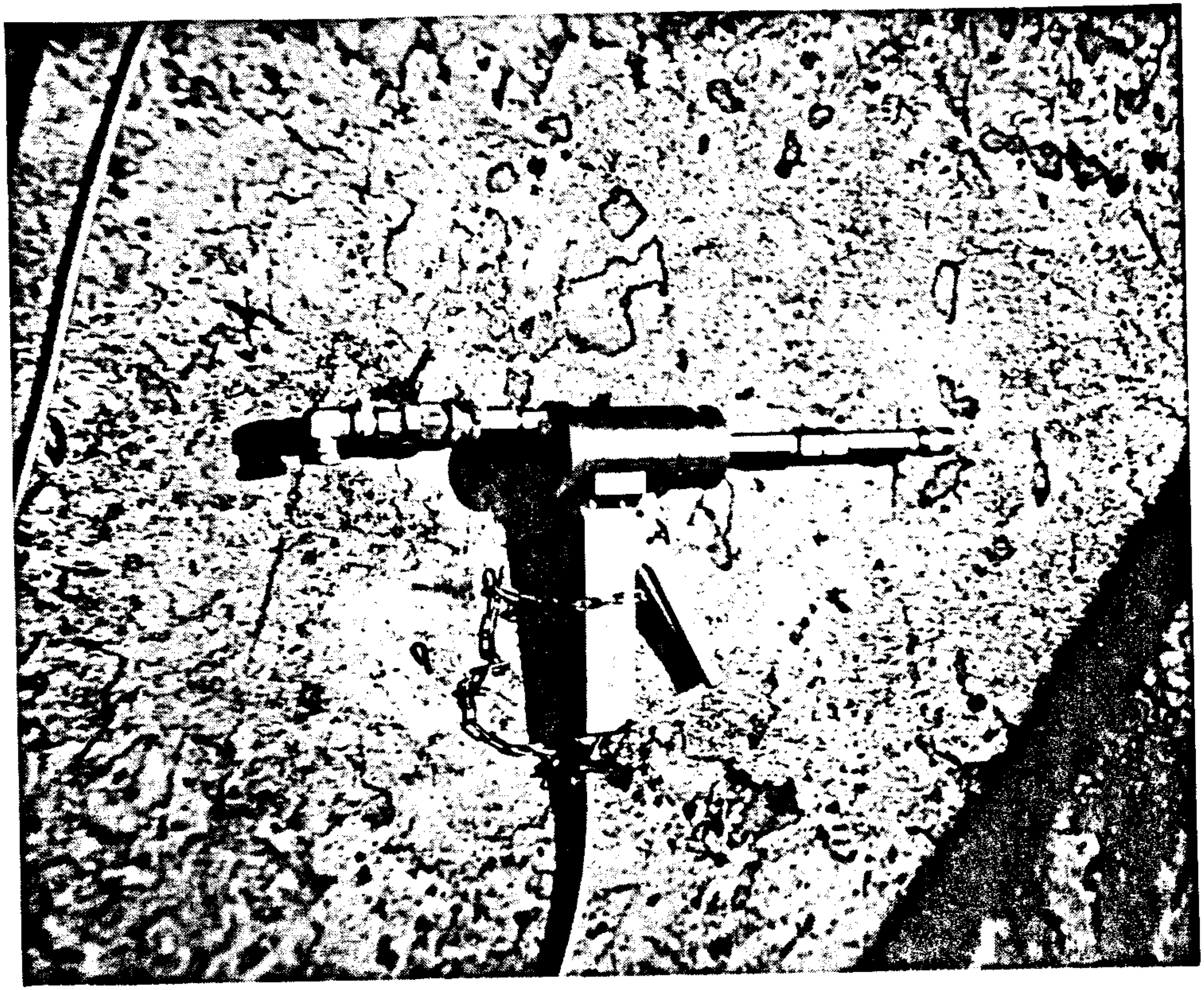


FIGURE 9 PHOTOGRAPH OF THE GUN AS IT WAS ASSEMBLED FOR USE.

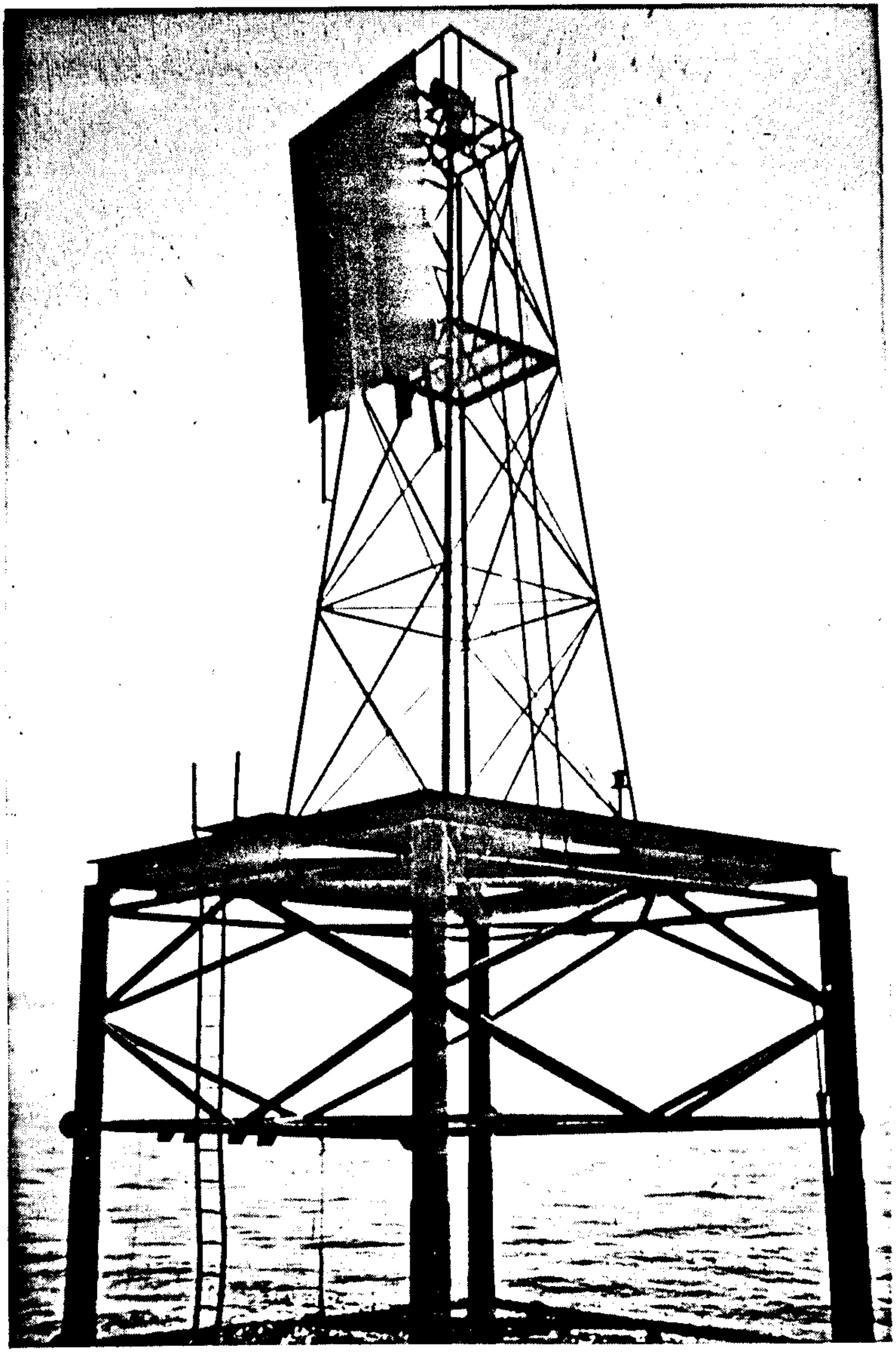


FIGURE 10 PHOTOGRAPH OF THE CHANNEL LIGHT STRUCTURE UTILIZED FOR TOWER CLEANING FIELD EXPERIMENTATION

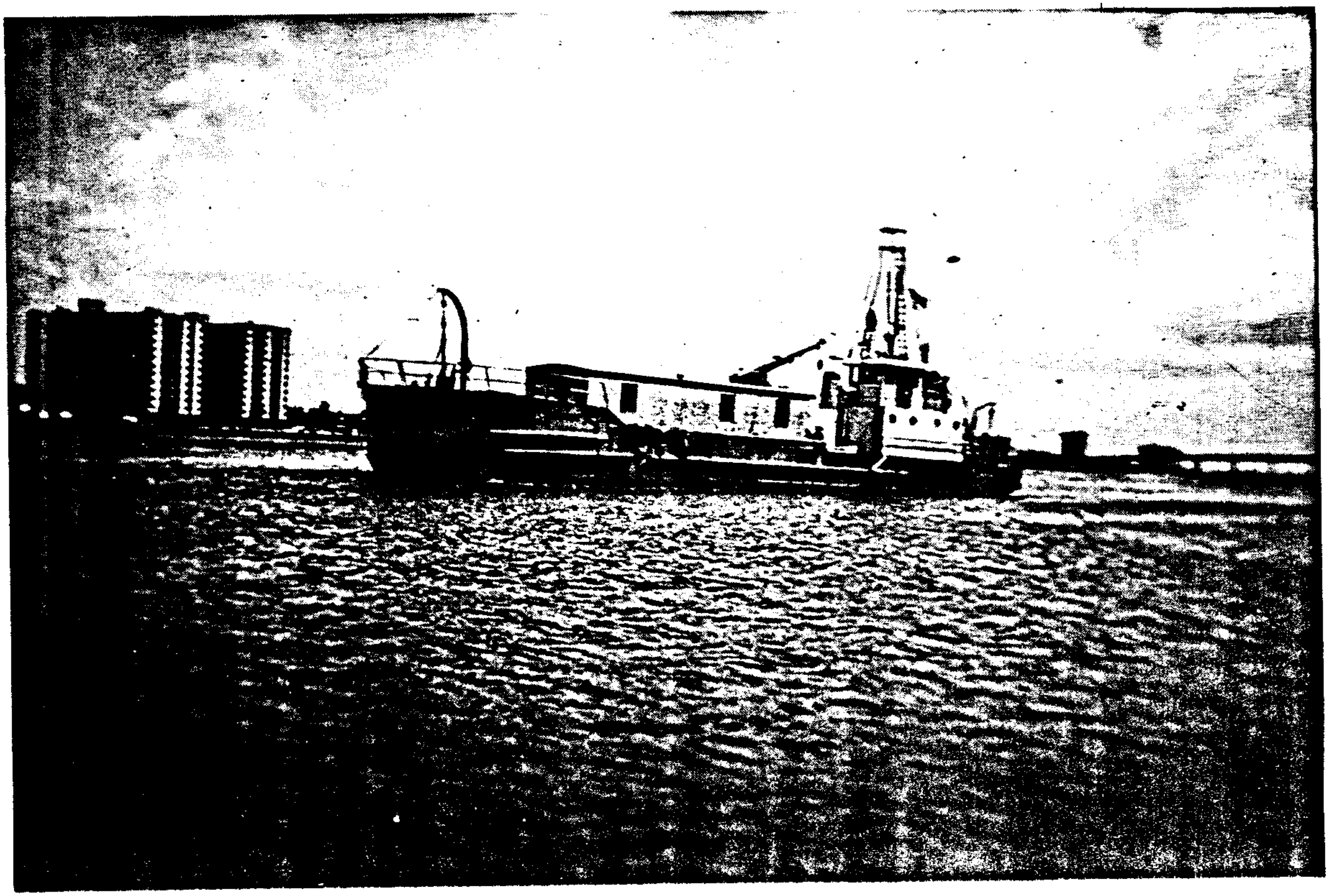
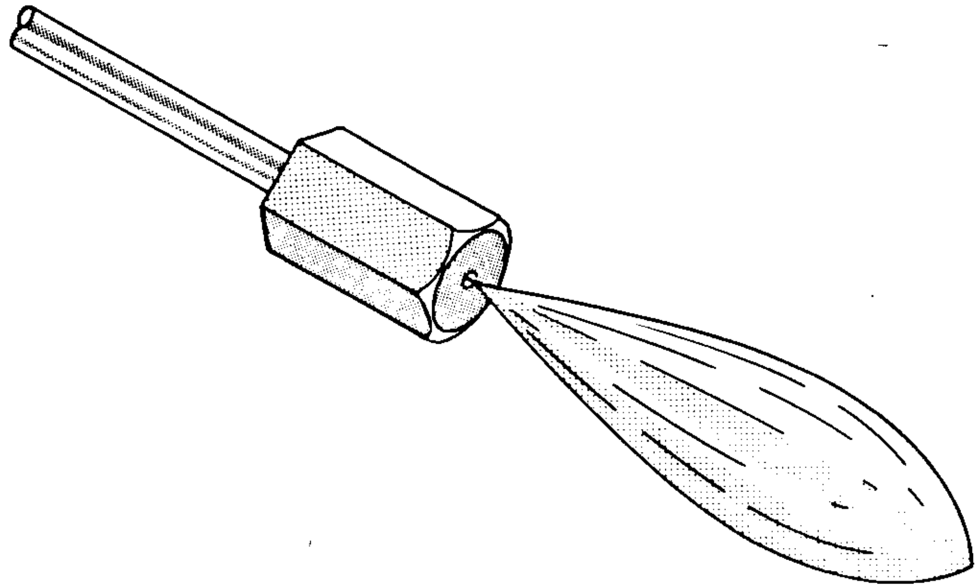
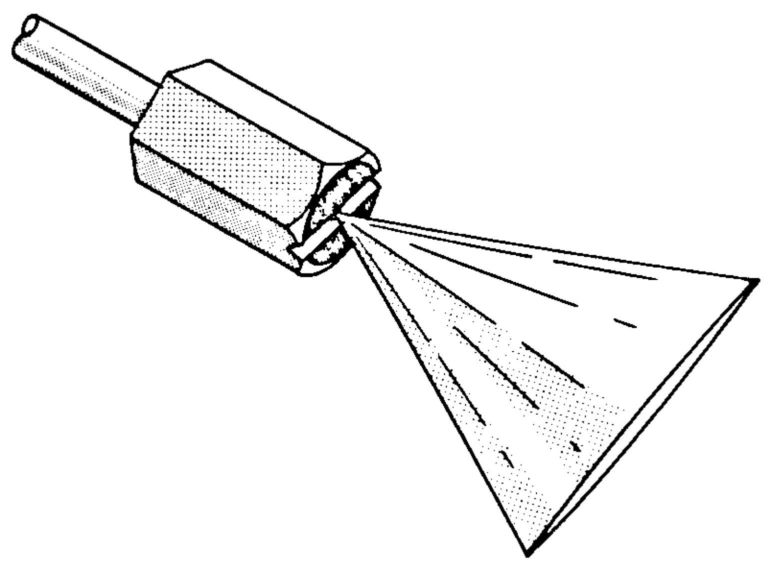


FIGURE 11 PHOTOGRAPH OF THE VESSEL WHICH SERVED AS WORK PLATFORM FOR FIELD OPERATIONS



CAVITATION ENVELOPE CREATED BY THE STANDARD ORIFICE NOZZLE



CAVITATION ENVELOPE CREATED BY THE FAN JET NOZZLE

FIGURE 12 ILLUSTRATION OF THE DIFFERENCE IN THE SHAPE OF THE CAVITATION ENVELOPE FORMED BY THE STANDARD ORIFICE NOZZLE AND THE FAN JET NOZZLE

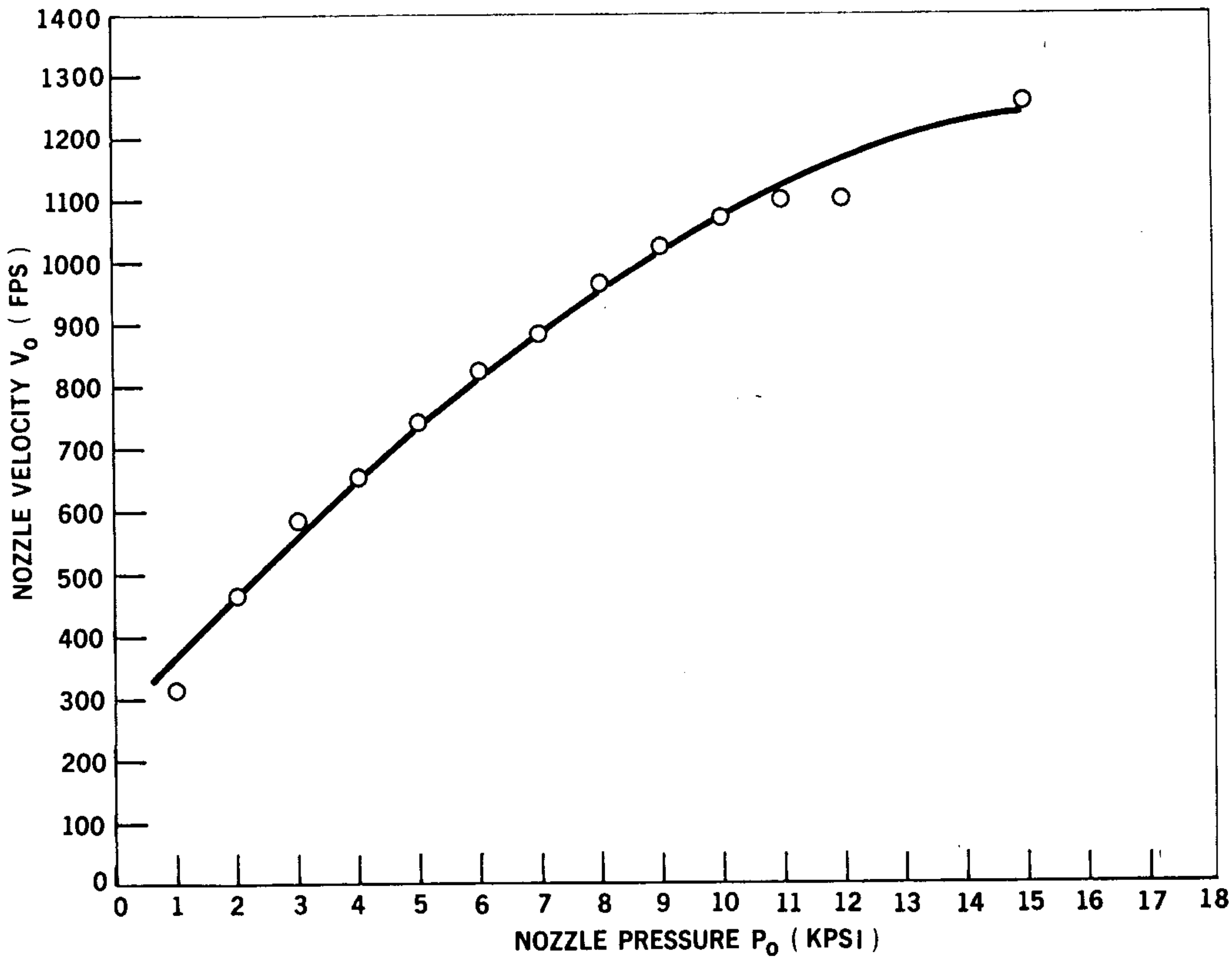


FIGURE 13 VELOCITY CALIBRATION WITH RESPECT TO PRESSURE FOR THE FAN JET NOZZLE DESIGN

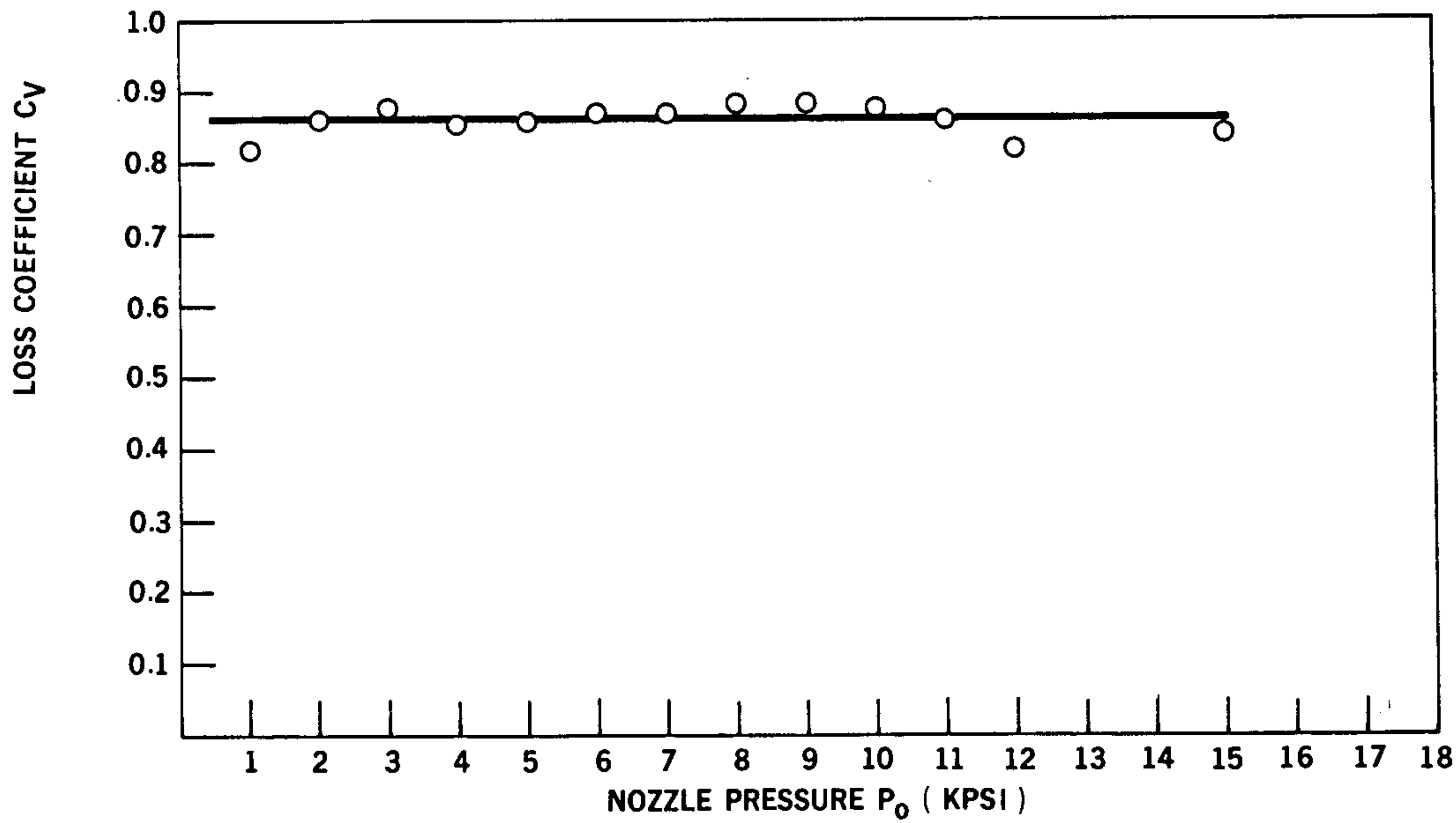


FIGURE 14 LOSS COEFFICIENT AS A FUNCTION OF PRESSURE FOR FAN JET NOZZLE DESIGN

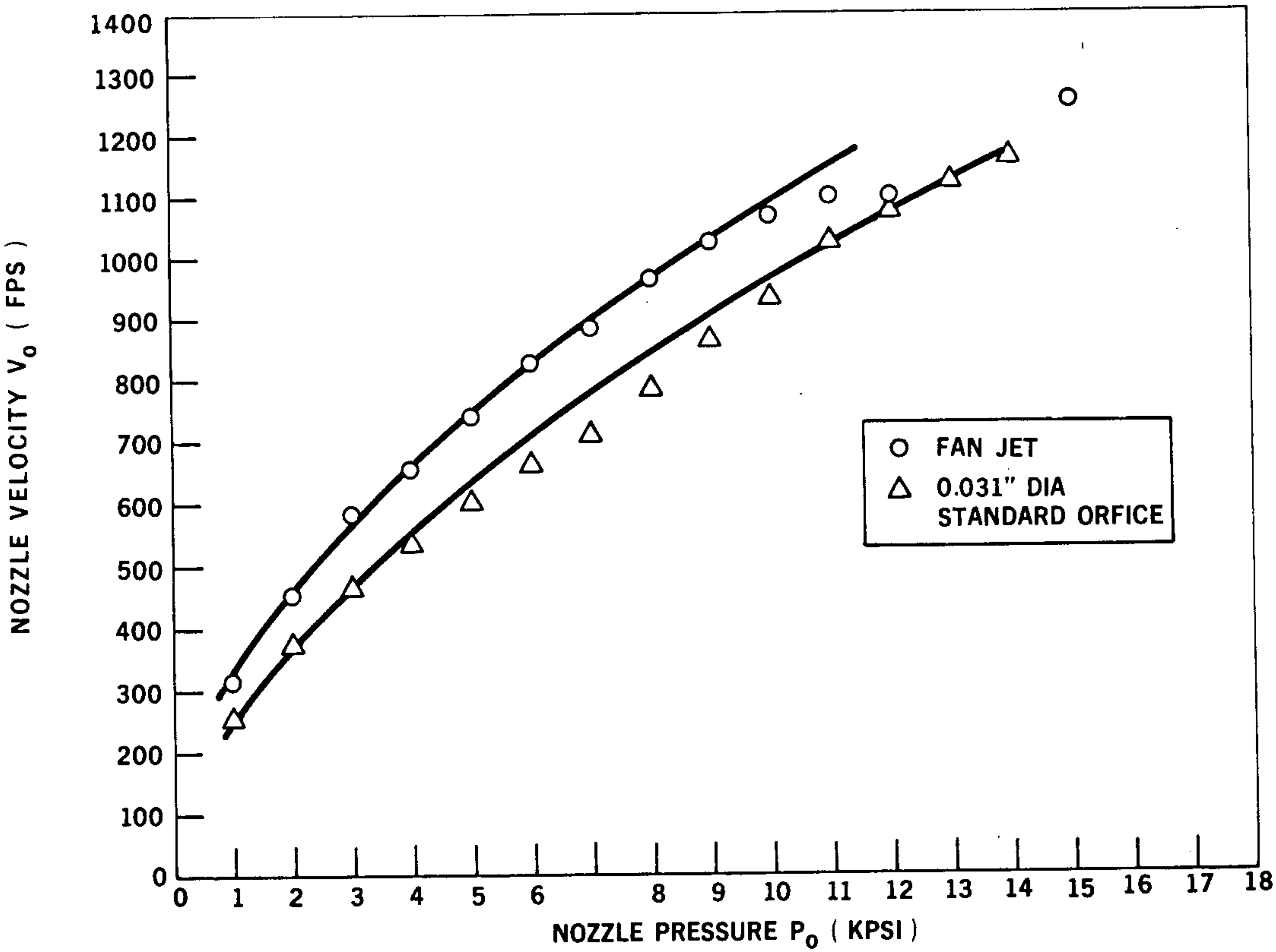


FIGURE 15 VELOCITY COMPARISON FOR THE TWO NOZZLE DESIGNS EVALUATED.

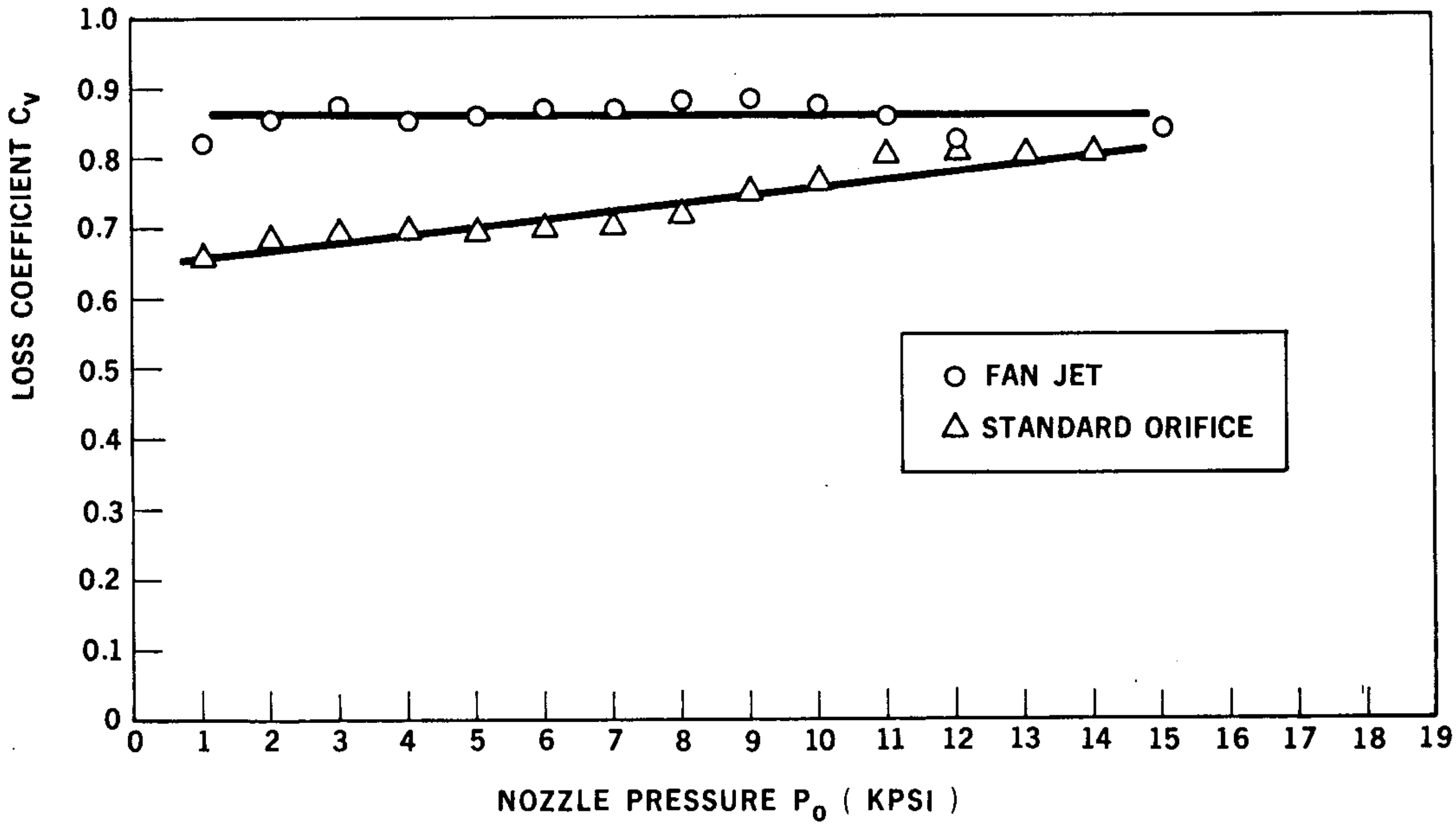


FIGURE 16 LOSS COEFFICIENT COMPARISON FOR THE TWO NOZZLE DESIGNS

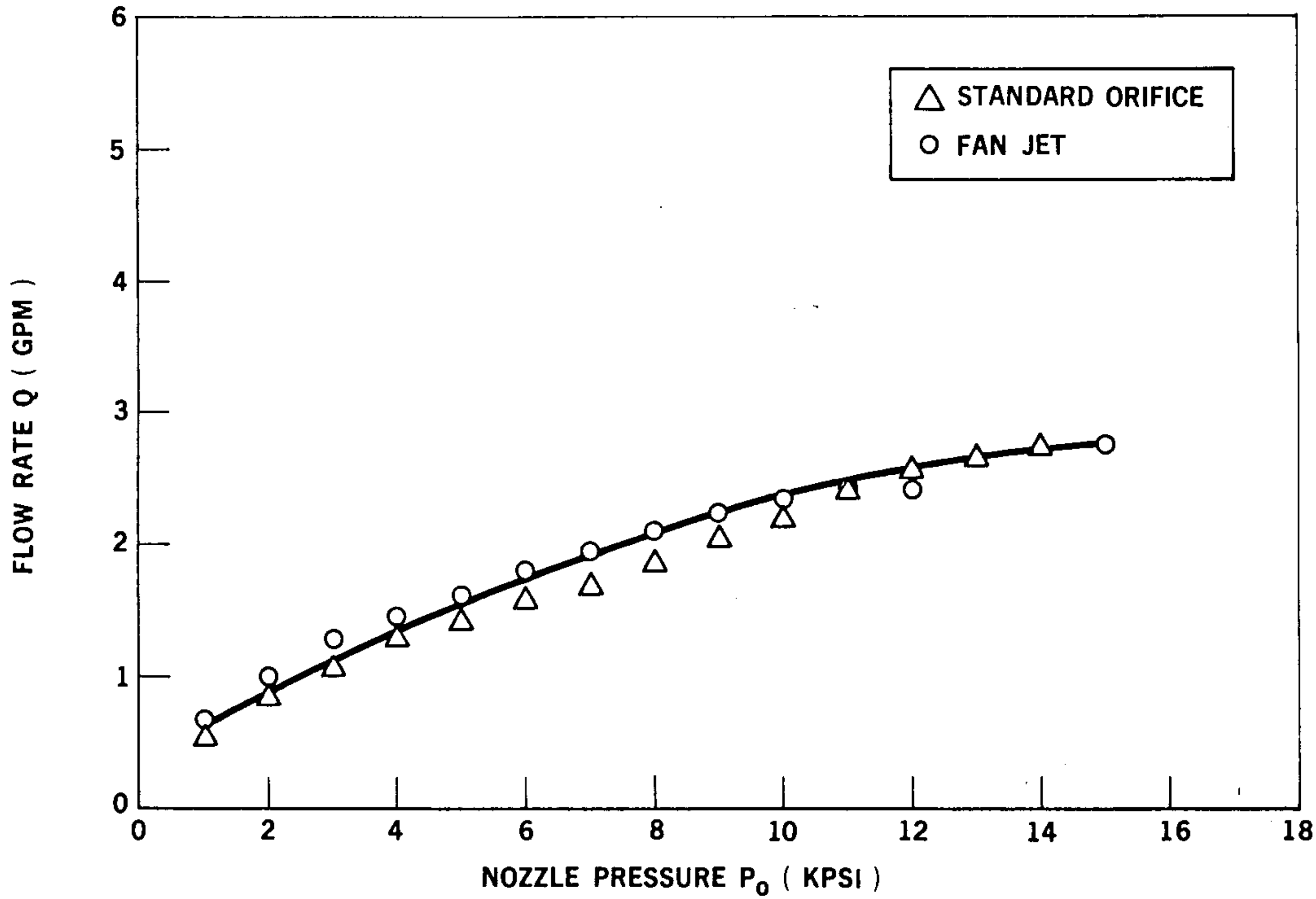


FIGURE 17 FLOW RATE COMPARISON FOR THE TWO NOZZLE DESIGNS

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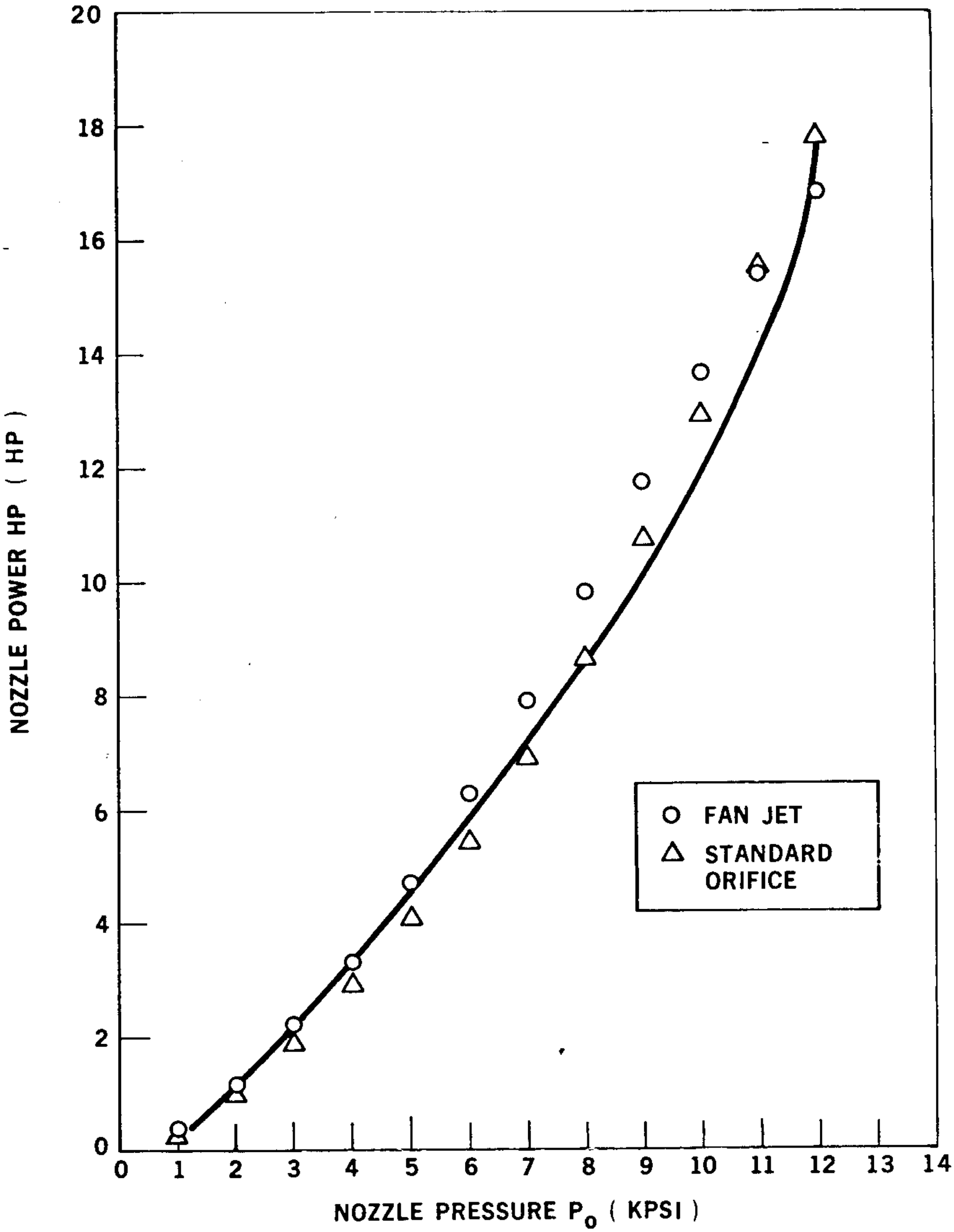

FIGURE 18 NOZZLE HORSEPOWER COMPARISON FOR THE TWO NOZZLE DESIGNS

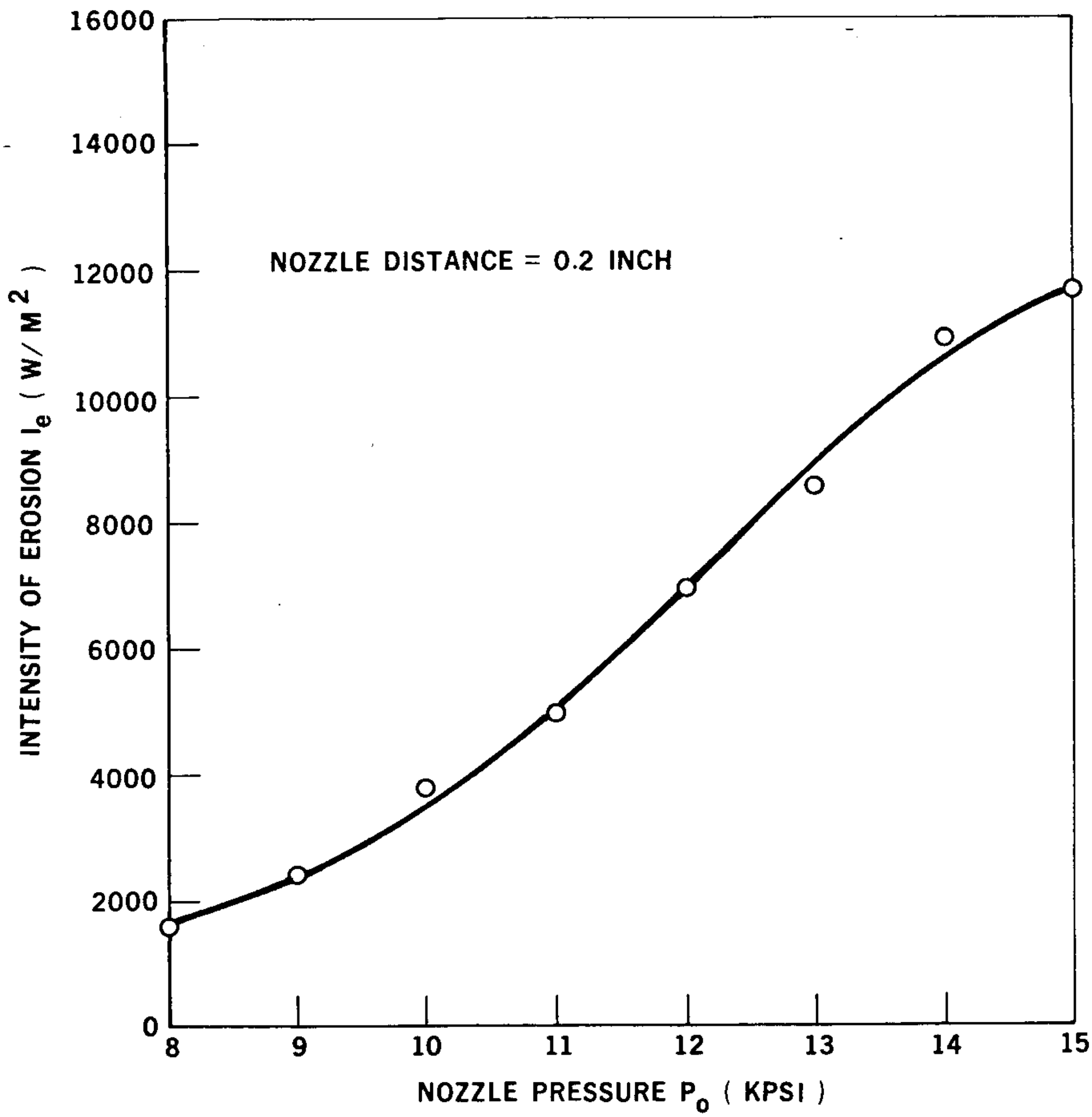

FIGURE 19 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE PRESSURE FOR THE FAN JET NOZZLE AT 0.2 INCH NOZZLE DISTANCE.

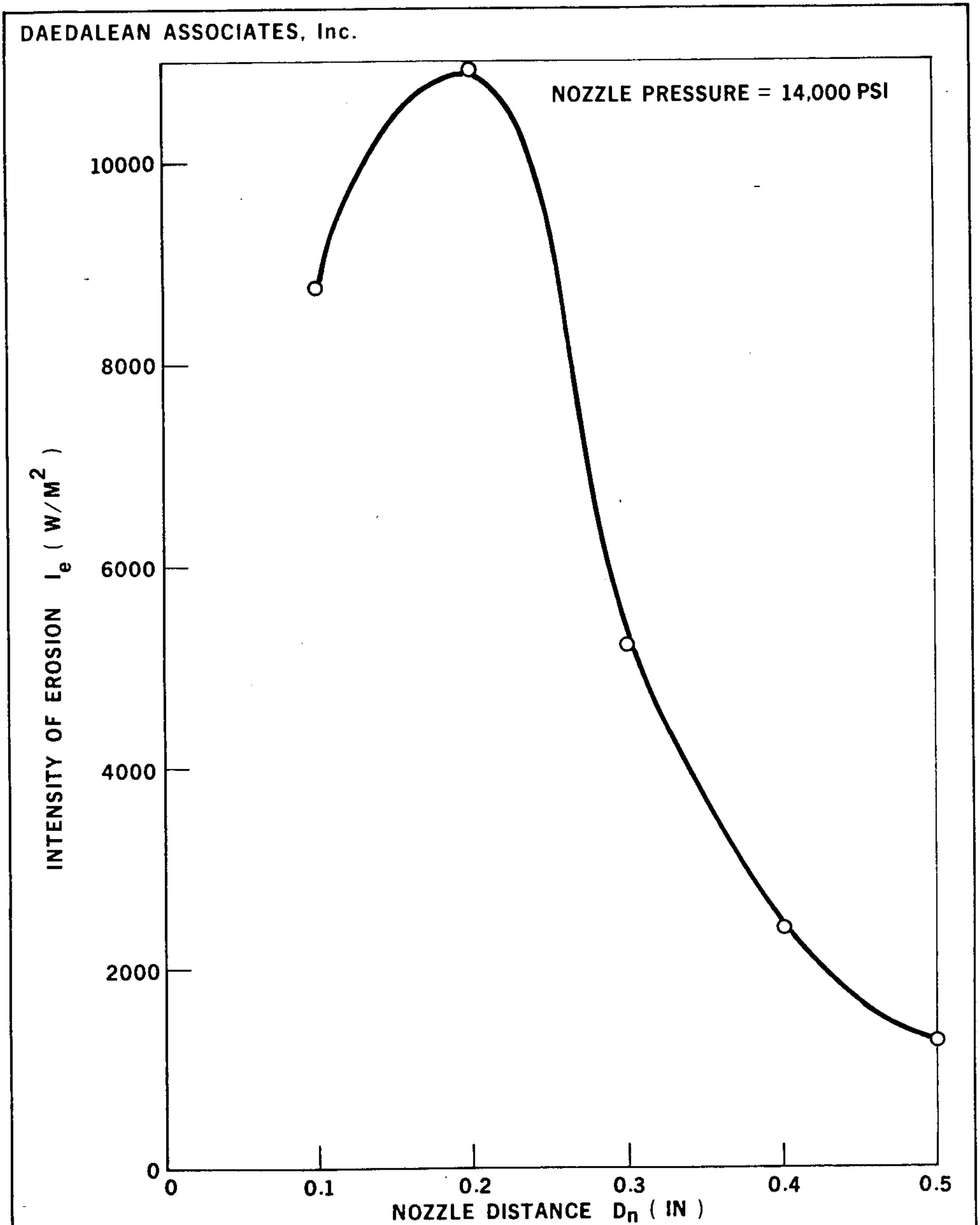

FIGURE 20 INTENSITY OF EROSION AS A FUNCTION OF NOZZLE STANDOFF DISTANCE FOR THE FAN JET AT 14,000 PSI NOZZLE PRESSURE

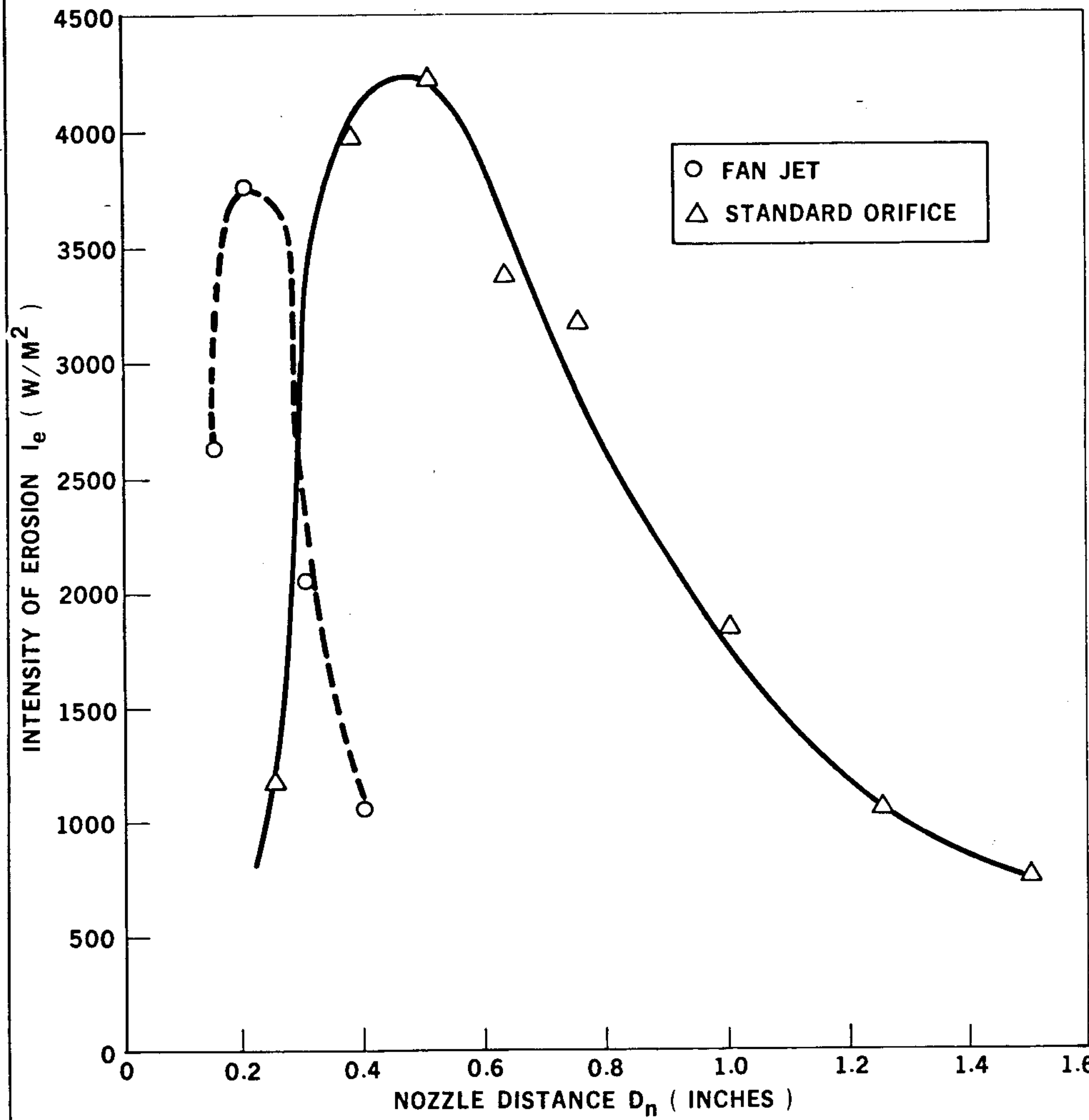

FIGURE 21 INTENSITY OF EROSION COMPARISON FOR TWO NOZZLE DESIGNS AT 10,000 PSI NOZZLE PRESSURE

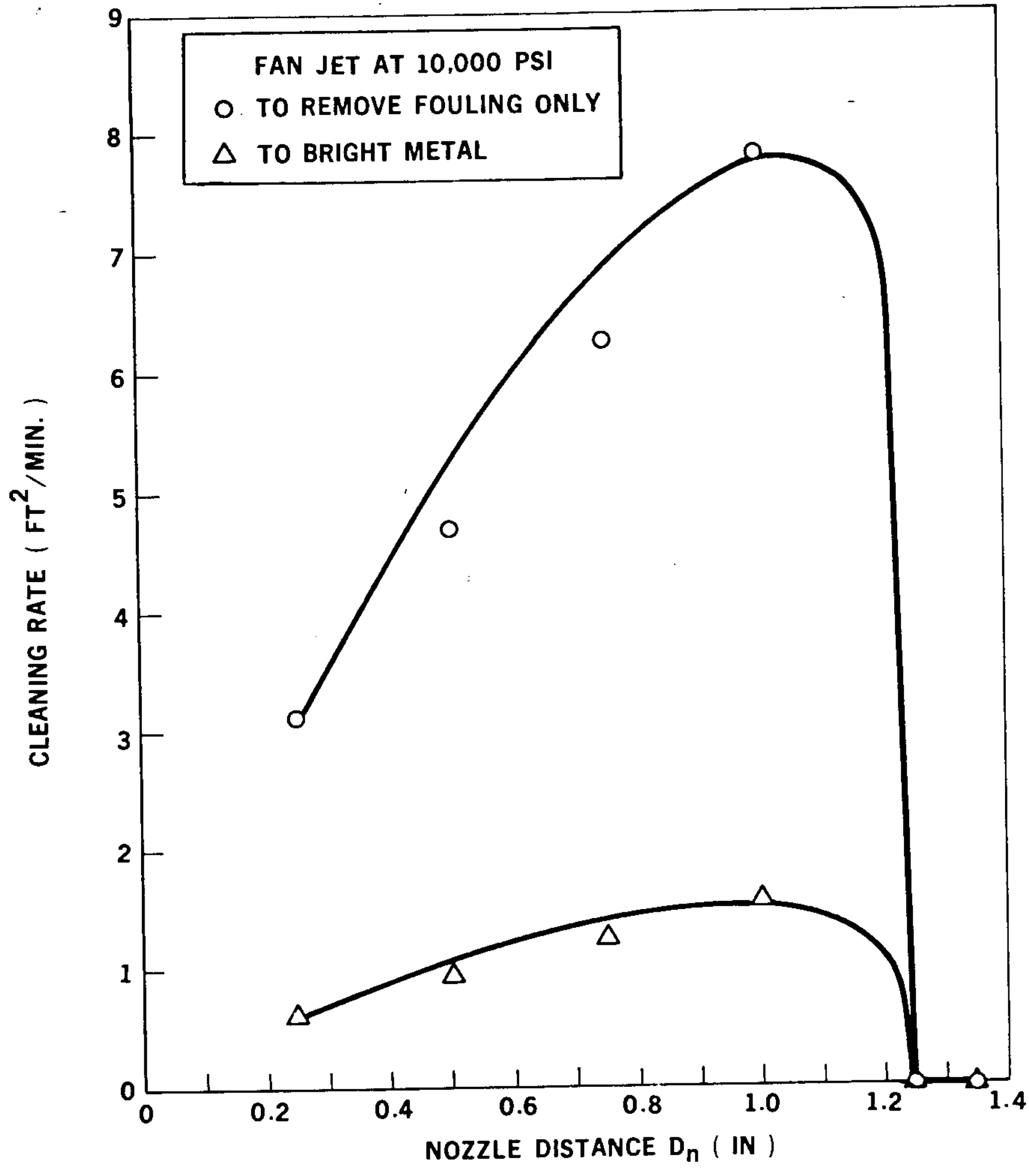

FIGURE 22 CLEANING RATE DATA FOR THE FAN JET AT 10,000 PSI FOR TWO TYPES OF CLEANING

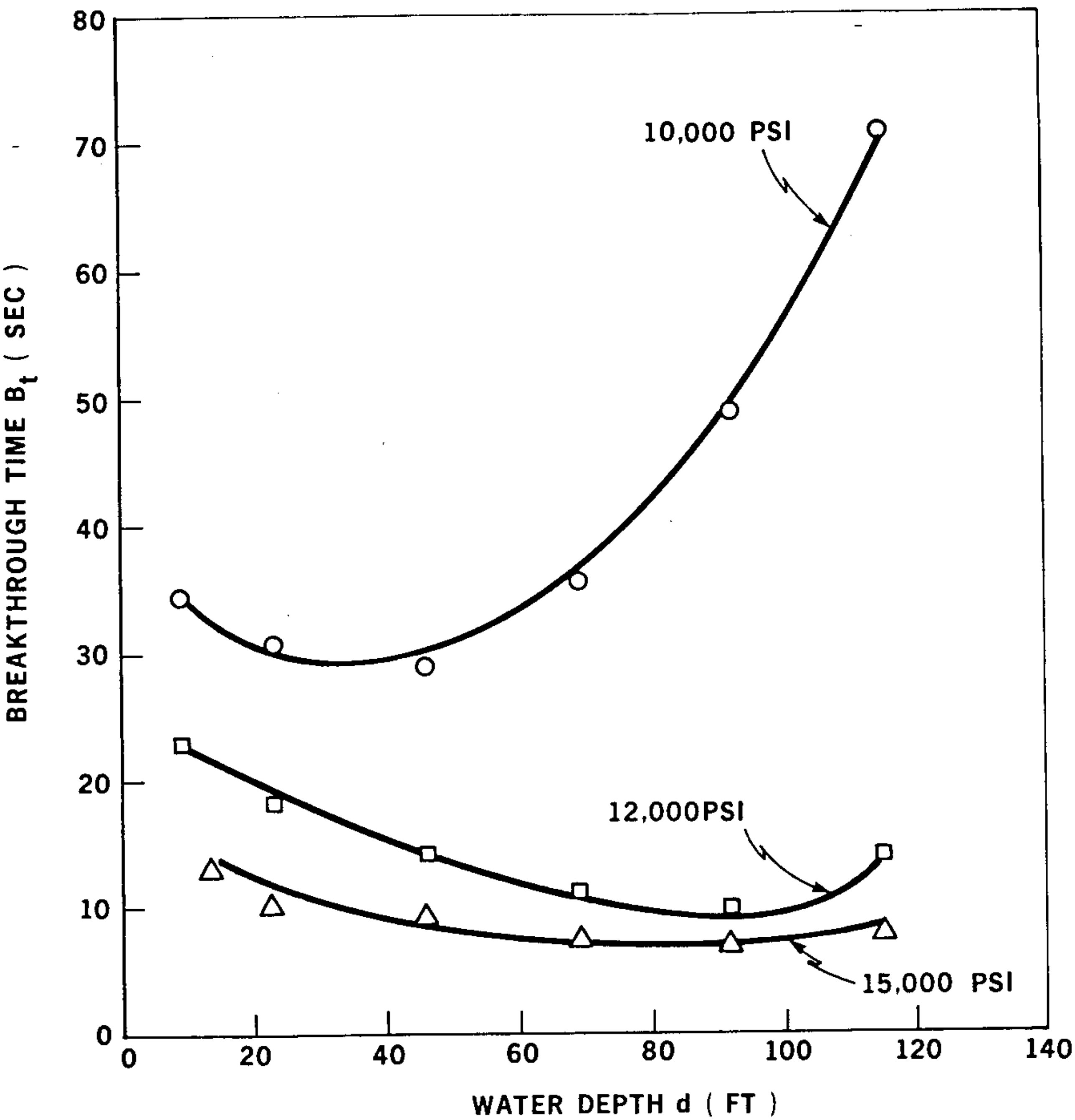

FIGURE 23 BREAKTHROUGH TIME AS A FUNCTION OF WATER DEPTH FOR THE STANDARD ASTM ORIFICE NOZZLE DESIGN AT 0.5 INCH NOZZLE DISTANCE AND VARIOUS NOZZLE PRESSURES.

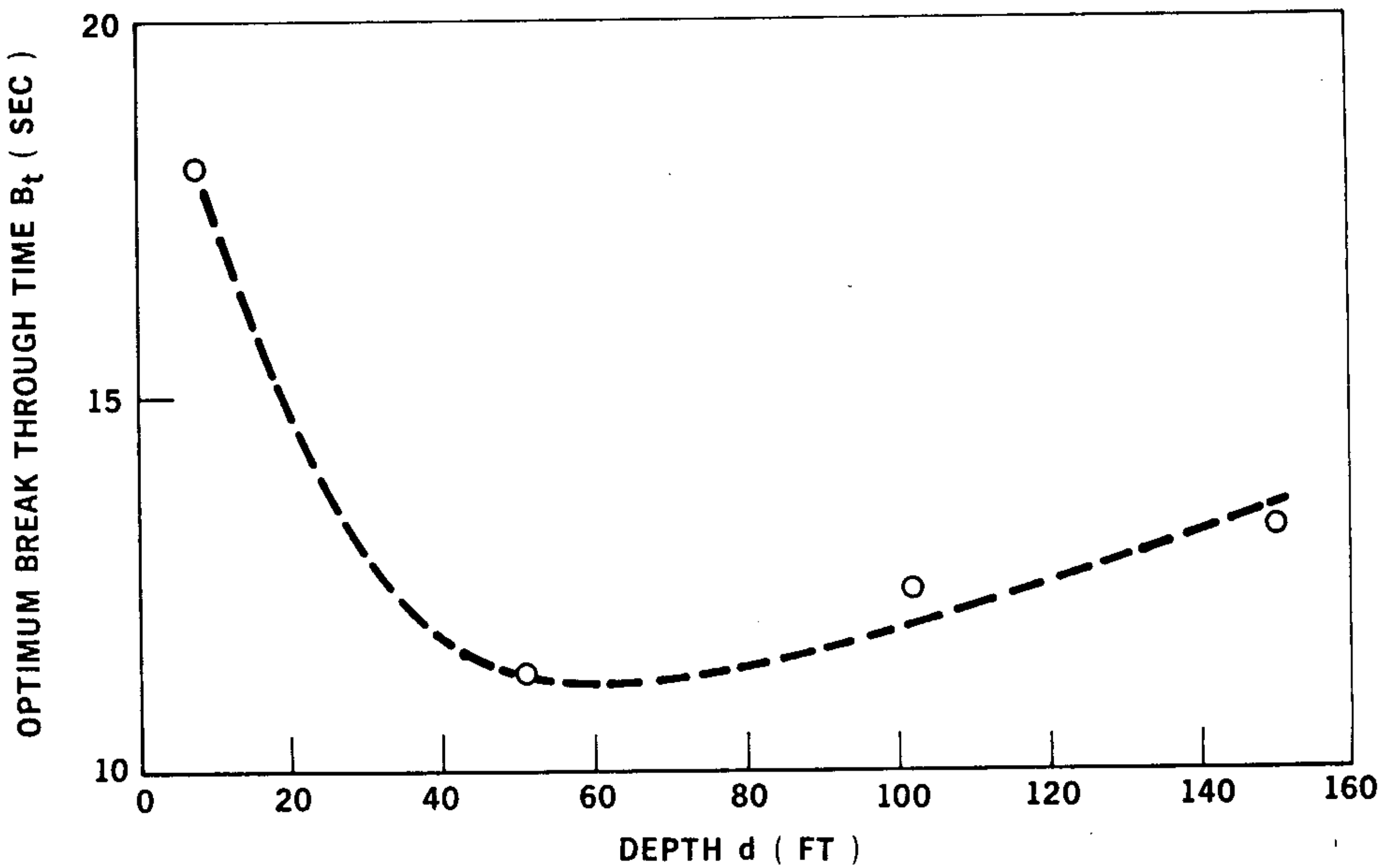

FIGURE 24 OPTIMUM BREAKTHROUGH TIME AS A FUNCTION OF WATER DEPTH FOR THE STANDARD NOZZLE DESIGN

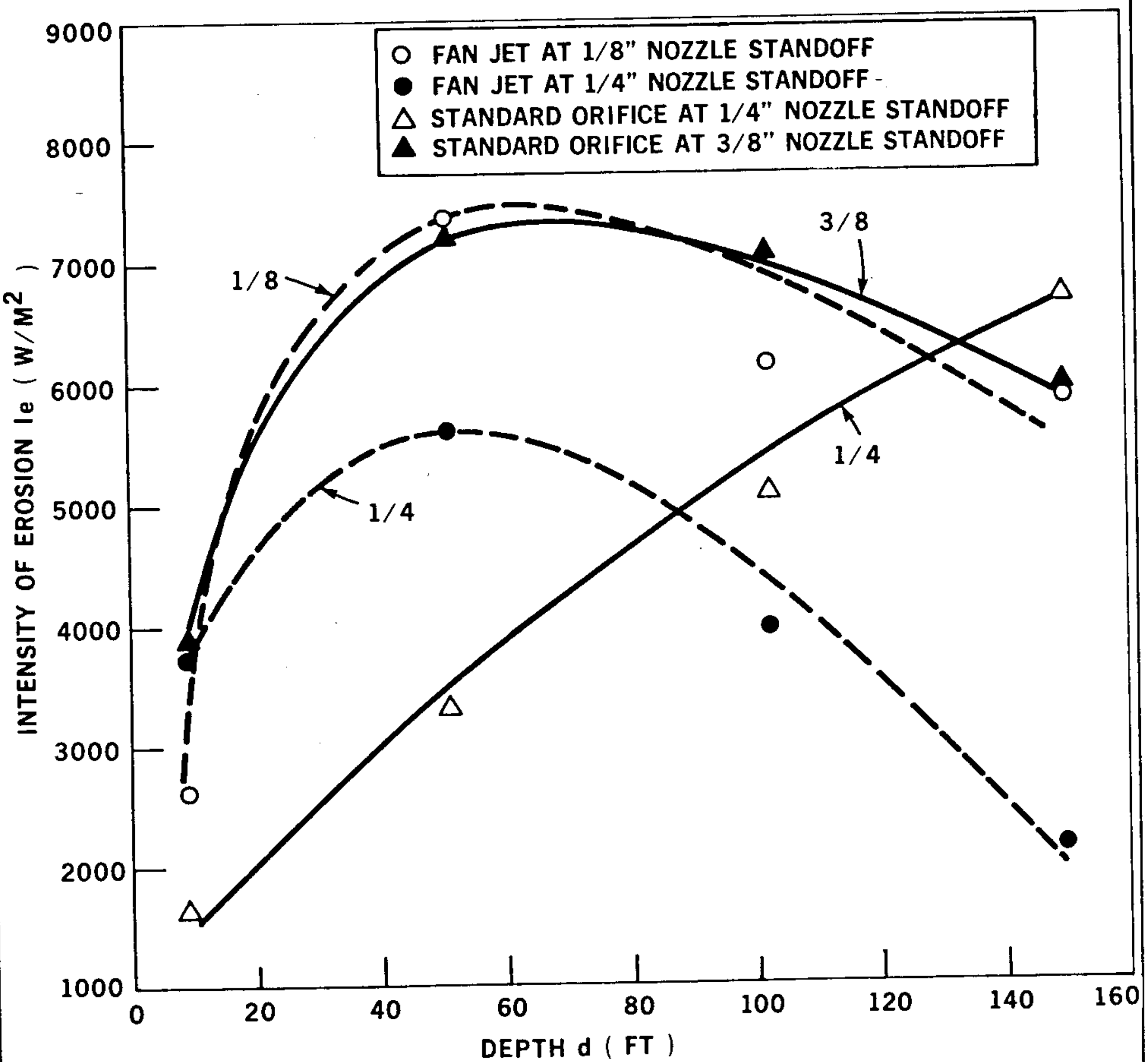

FIGURE 25 INTENSITY OF EROSION AS A FUNCTION OF WATER DEPTH COMPARISON FOR THE TWO NOZZLE DESIGNS EVALUATED.

FIGURE 26 PHOTOGRAPH OF THE SECTION OF PIPE CLEANED AS A PORTION OF THE FIELD TESTING.

APPENDIX A

APPENDIX A

DESCRIPTION OF CAVITATION PHENOMENA

In most engineering contexts, cavitation is defined as the process of formation of the vapor phase of a liquid when it is subjected to reduced pressures at constant ambient temperature. In general, a liquid is said to cavitate when vapor bubbles are observed to form and grow as a consequence of pressure reduction. When the phase transition is a result of pressure change by hydrodynamic means, a two-phase flow composed of a liquid and its vapor is called a cavitating flow. While these definitions imply a distinction between phase transitions associated with reduction of pressure, on the one hand, and addition of heat (i.e. boiling), on the other, heat-transfer effects may play an important role in many cases of cavitating liquids. Such effects are especially of importance in liquids near their boiling points. From a purely physical-chemical point of view, of course, no distinction need be made between boiling and cavitation, at least insofar as the question of inception is concerned, and many of the basic physical ideas regarding inception, vapor mass transfer, and condensation apply equally.

As cavitation just begins, tiny vapor bubbles form in rapid succession at the point of lowest pressure and are carried downstream by the flow into a zone of higher pressure, where they immediately collapse as the vapor within them condenses. The process of formation and collapse is so nearly instantaneous that with the naked eye only a continuous opaque blur can be distinguished. However, as each of the countless individual bubbles collapse, the resulting impact of opposing masses of liquid produces an extremely great local pressure which is transmitted radially outward with the speed of sound, followed by a negative pressure wave which may lead to one or more repetitions of the vaporization-condensation cycle. Boundary materials in the immediate vicinity are, therefore, subject to rapidly repeated stress reversals and may eventually fail through fatigue. This failure of the material is cavitation erosion.

An increase in the velocity of flow beyond that required for incipient cavitation can produce no further reduction in pressure at the point of cavitation, but merely an elongation of the zone over which the vapor limit prevails. At the same time the size of the vapor bubbles increases, until at advanced stages a more or less stable vapor pocket is formed, which is very similar in shape to the zone of separation next to an unstreamlined boundary. Since the formation of such a pocket must result in a change of the surrounding flow pattern, it is to be expected that the pressure distribution will change accordingly, the pressure necessarily remaining at its vapor limit throughout the length of the cavitation pocket.

For the purposes of this program, the phenomena of cavitation is the formation, growth and collapse of vapor cavities formed from nuclei. Water will provide the continuous medium for the cavitation process. As the vapor cavities collapse in the vicinity of the cavity envelope perimeter, the material is eroded from the surface upon which the jet impinges (Figure A-1). Figure A-2 is a photographic representation of the cavity envelope during which the cavitation process is developed. The process is initiated from a nuclei which forms, grows to critical size and collapses. Recent experiments conducted at the DAEDALEAN facility have determined the feasibility of this process as a method of effectively eroding the marine growth from offshore structures so that those structures can be inspected.

CAVITATION INCEPTION PARAMETER

A useful index for the cavitation phenomenon is formulated by introducing for the symbol P in the pressure parameter its minimum value P_v, the result being called the cavitation number:

$$\sigma = \frac{P_o - P_v}{\frac{1}{2}\rho \; V_o^{\,2}} \qquad [1]$$

where: P_o = free stream pressure

P_v = vapor pressure of liquid

V_o = free stream velocity

ρ = density of liquid

So long as σ has an appreciably greater numerical value than the minimum ordinate on the dimensionless pressure-distribution curve for a body of given form, the occurrence of cavitation is not to be expected at any point on the boundary. Once σ becomes approximately equal in absolute magnitude to the minimum ordinate, on the other hand, conditions of incipient cavitation should prevail, and at values of σ below this critical limit σ_i a marked effect upon the pressure distribution is to be expected (8).

In the case of body forms which result in separation, it is to be noted that cavitation will generally begin within the fine-scale eddies formed at the separation surface long before the boundary pressure attains its vapor limit. As a result, it is then not possible to predict the magnitude of σ_i either by analytical means or by actual measurement of the pressure distribution in flow without cavitation. On the other hand, not only are boundary forms which properly guide the flow most subject to analytical determination, but they are also those least subject to cavitation. The process of streamlining, in other words, simultaneously lowers the magnitude of σ_i (i.e., the tendency toward cavitation) and makes it more accurately predictable by analytical means.

The cavitation inception parameter is to be experimentally determined in order to evaluate the optimum operating parameters and the efficiency of cleaning by the cavitating jet technique.

CAVITATING JET CLEANING TECHNIQUE

Cavitation cleaning is caused by the collapse of bubbles at or near the solid boundaries guiding high speed flow. Since the early cavitation experiences were encountered on ship propellers in a corrosive medium (seawater), there were some controversies as to whether the mechanism was corrosion or mechanical removal. However, it is now generally accepted that the high pressures caused by the collapse of bubbles produce mechanical removal of material. During the process of cavitation a certain volume of material is removed from the surface as a result of the work done by the bubble collapse forces. The energy absorbed by the material is given by:

$$E = \Delta V \bullet S \qquad [2]$$

where: E = energy absorbed by the material removed

ΔV = volume of material removed

S = scale strength which represents the energy absorbing capacity of the material per unit volume under the action of the forces.

The intensity of cavitation is then defined as the power absorbed by the material per unit area and given by:

$$I = \frac{\Delta V \bullet S}{A \bullet \Delta t} \quad [3]$$

or

$$I = \frac{\Delta y}{\Delta t} \quad S \quad [4]$$

where: A = area of cleaning

Δy = mean depth of scale = $\frac{\Delta V}{A}$

Δt = exposure time

This is the output intensity of cleaning as seen by the material; similarly one can derive an expression for the bubble collapse intensity which is the input to the cleaning process.

$$\left(\frac{\Delta y}{\Delta t}\right) \bullet \left(S\right) \quad \alpha \quad (P_i) \bullet (R) \bullet (n) \quad [5]$$

where: P_i = impact pressure

R = size of the bubble or jet

n = number of impacts per unit time

These ideas have been incorporated into a master chart for cavitation erosion as shown in Figure A-3 (9). In this chart, the intensity of erosion is plotted against the rate of mean depth of erosion for various materials ranging from soft lead to very highly stellites. The range of intensities typical of practical machines varies from 10^3-10^{-4} in.-lb/year-in.^{2}. The screening tests such as the vibratory test and rotating disk test operate at intensity levels on the order of 10^5 in.-lb/year-in.^{2} (1 watt/m^2). The depth of erosion is generally in the range of a fraction of an inch per year. Chemical corrosion rates on steels are in the range of 10^{-3}-10^{-2} in. per year (ipy). Erosion rates on the order of 1 ipy represent serious erosion which may warrant operational limitation or redesign.

The level of threshold intensities for various metals are on the order of 10^{-1} w/m^2 at the most. Elimination of cavitation by the substitution of one metal for another is possible only up to this level of intensity. For this reason, the usefulness of cathodic protection also seems to be limited at this level. If one is prepared to tolerate some erosion and periodic maintenance, then the materials selected coupled with cathodic protection can possibly extend the allowable intensity levels up to 1 w/m^2. However, if the intensity levels are higher than these values, then the foregoing protection methods may not work. In such cases, hydrodynamic redesign, air injection, and specifying limits for operation are the alternate remedial possibilities.

Another tool for the benefit of designers and operators is a multipurpose nomogram as shown in Figure A-4. It provides a visual idea of the range of intensities encountered in actual practice within the range of the depth of cavitation material used and time of operation. It also provides a quick and easy method of estimating the intensity of cavitation for a field installation. Lastly, the selection of better materials, if available, is easily made.

From such tools as the master chart and the nomogram, it is possible to estimate the intensity of cavitation required to remove the marine growth and fouling most efficiently at the optimum rate of cleaning without damage to the platform structure. The intensity of cleaning can be adjusted to the required level.

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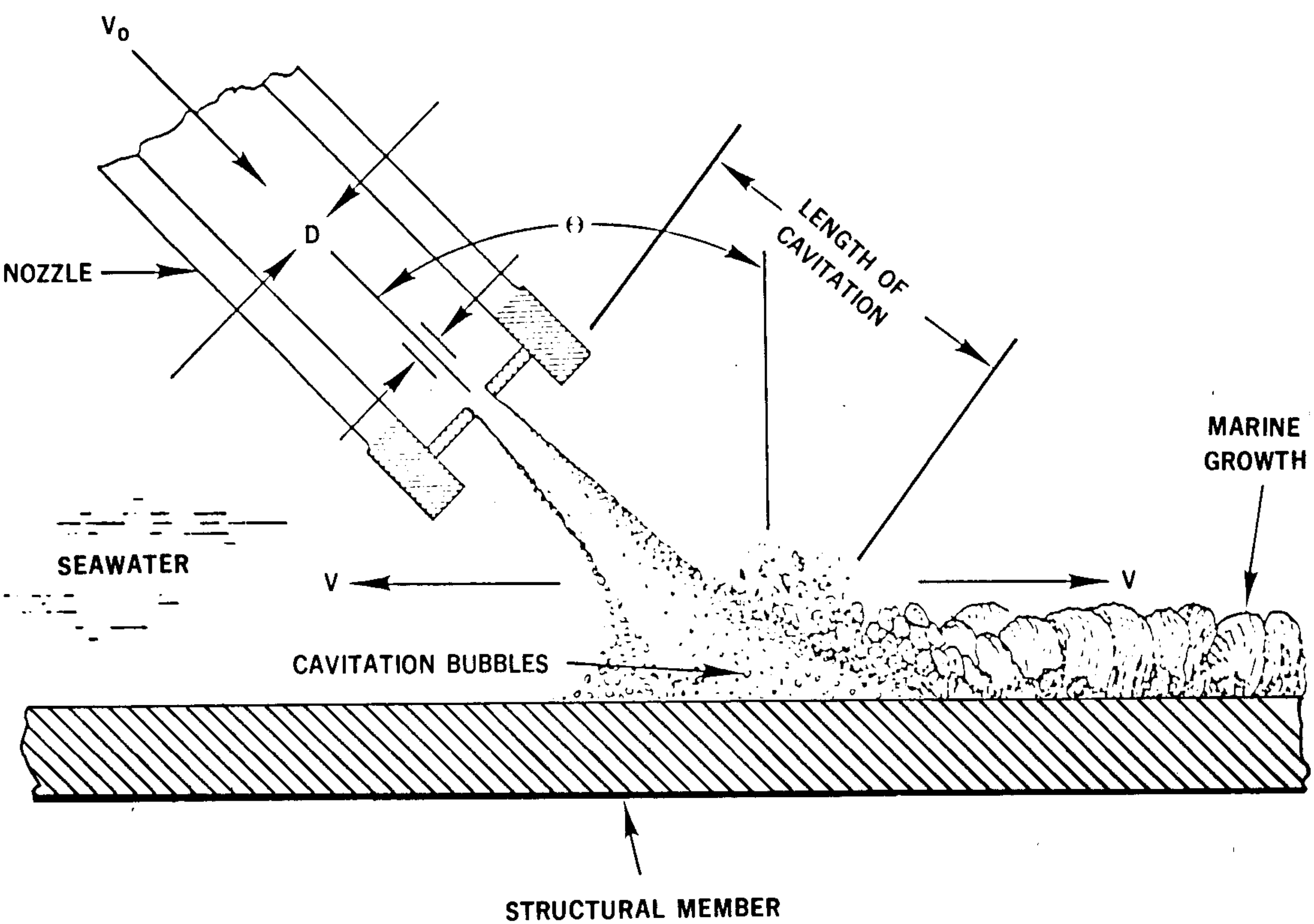

FIGURE A-1 PRINCIPLE OF CONTROLLED CAVITATION CLEANING TECHNIQUE AS APPLIED TO REMOVAL OF MARINE GROWTH AND FOULING FROM OFFSHORE PLATFORM STRUCTURAL MEMBER

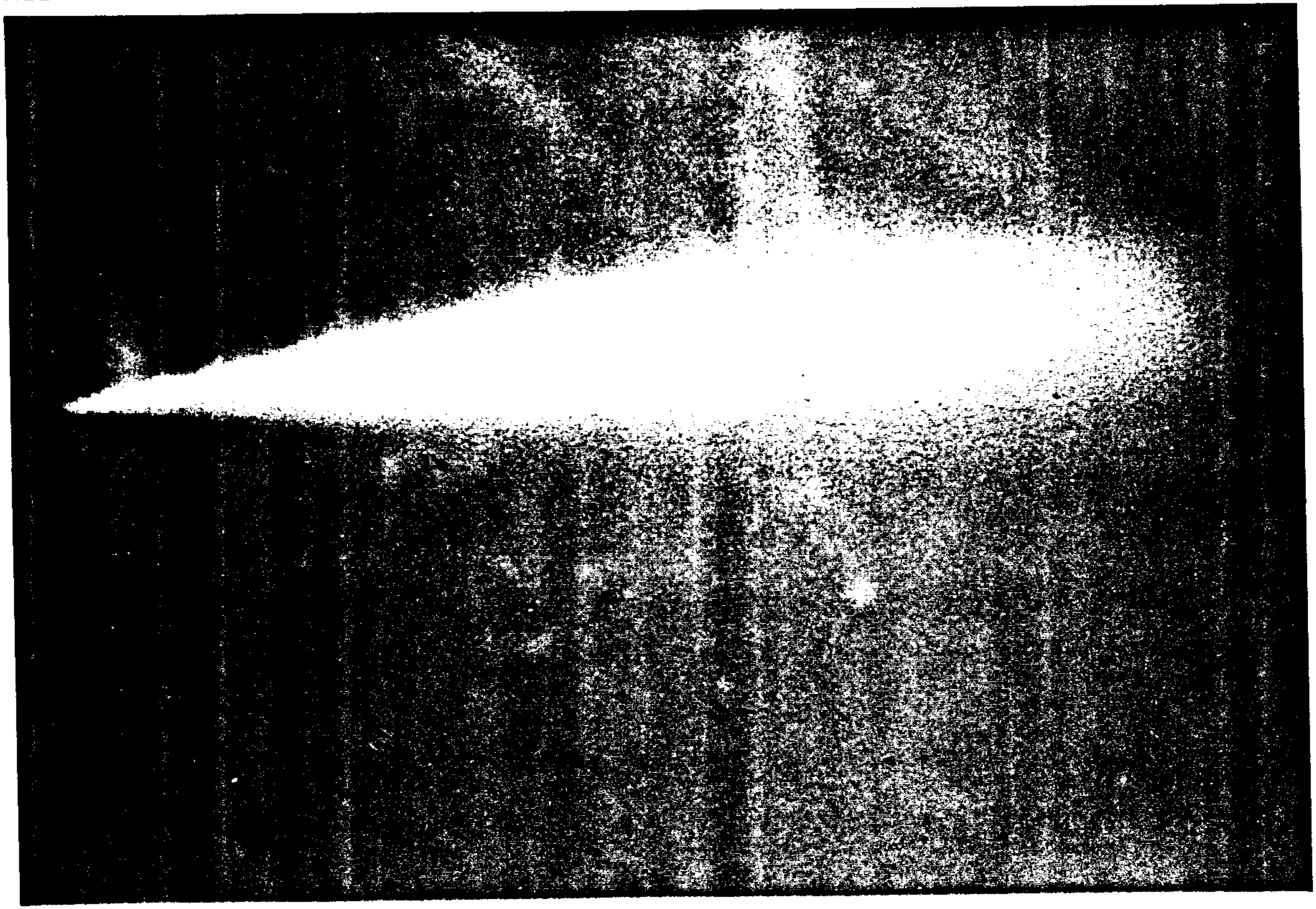

FIGURE A-2 PHOTOGRAPHIC REPRESENTATION OF THE CAVITATING ENVELOPE DURING WHICH TIME THE BUBBLES FORM A NUCLEI, GROW TO CRITICAL SIZE AND COLLAPSE IN THE CONTINUOUS CAVITATION PROCESS

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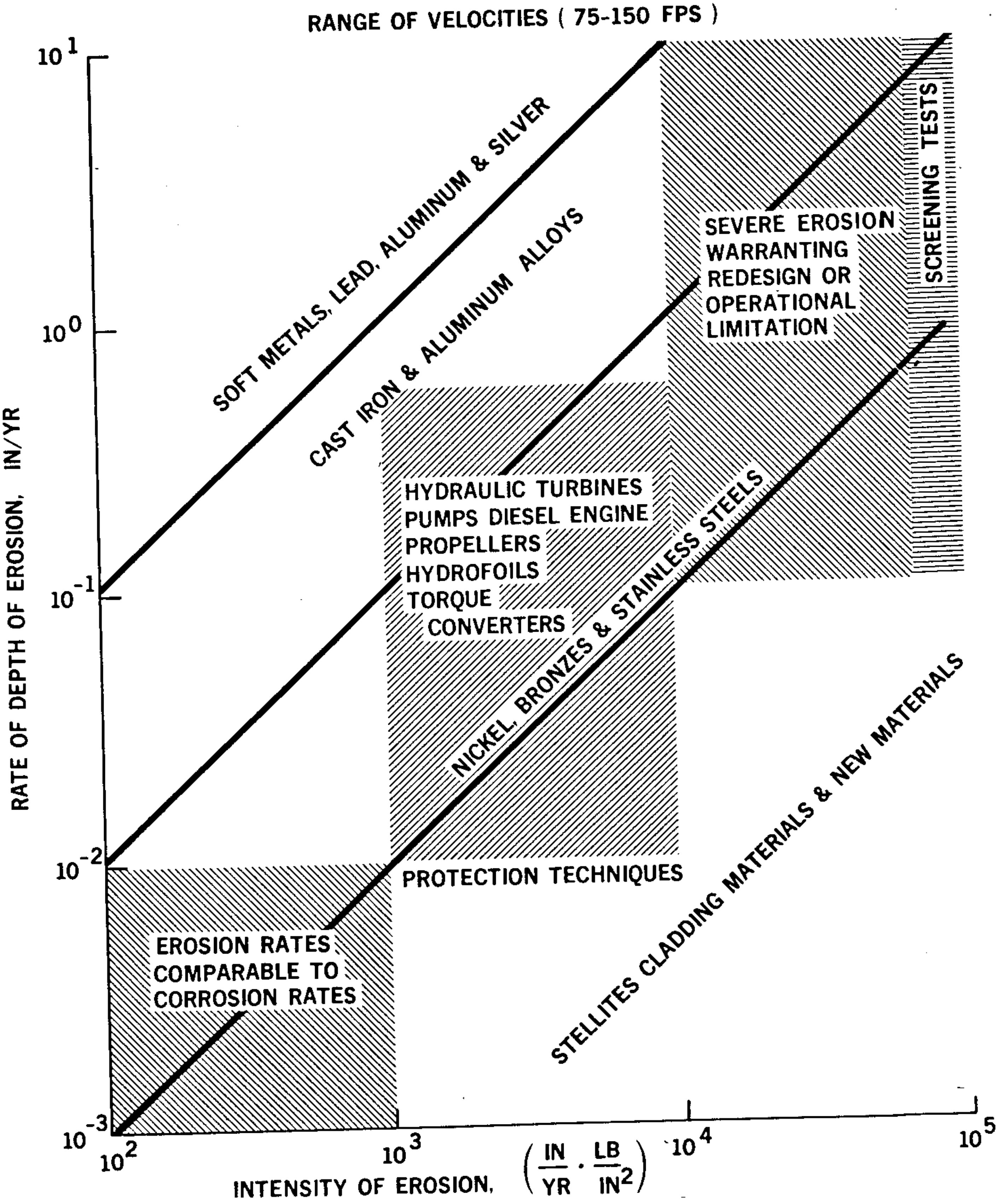

FIGURE A-3 MASTER CHART FOR CAVITATION EROSION

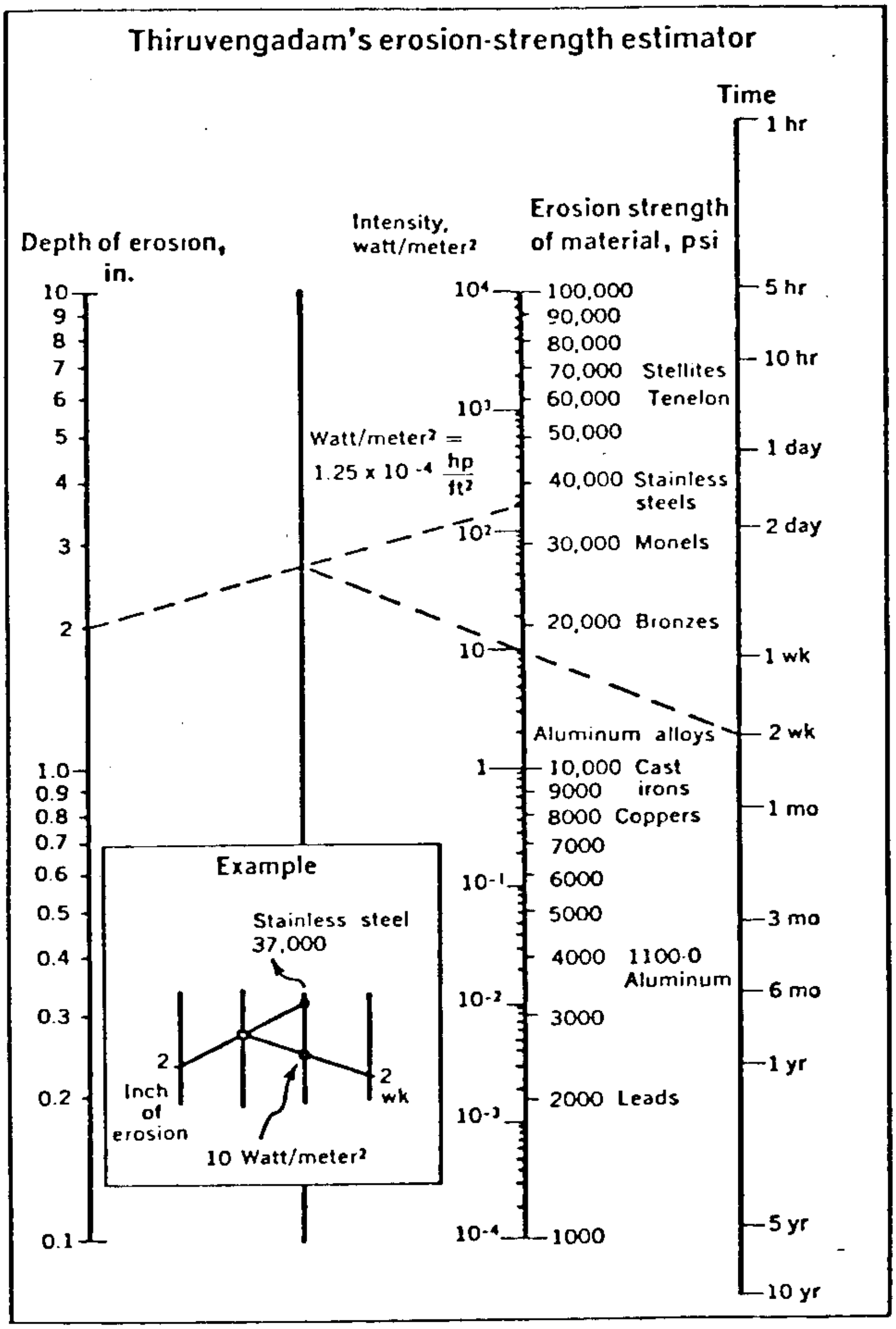

FIGURE A-4 EROSION INTENSITY ESTIMATOR

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